



Human Systems Integration (HSI) Practitioner's Guide

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Human Systems Integration (HSI) Practitioner's Guide

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ACRONYMS AND ABBREVIATIONS

AFE	Aircrew Flight Equipment
AFMC	Air Force Materiel Command
AFRL	Air Force Research Laboratory
AIP	Acquisition Improvement Plan
ANSI/AIAA	American National Standards Institute/American Institute of Aeronautics and Astronautics
ARMC	Air Force Materiel Command
ASD	Aeronautical Systems Division
Assy	Assembly
ATF	Advanced Tactical Fighter
BOS	Back-up Oxygen System
CARD	Constellation Architecture Requirements Document
CCB	Configuration Control Board
CCP	Commercial Crew Program
CDR	Critical Design Review
CERR	Critical Events Readiness Review
CEV	Crew Exploration Vehicle
CHMO	Chief Health and Medical Officer
CMO	Chief Medical Officer
ConOps	Concept of Operations
CoP	Community of Practice
COTS	Commercial Off-The-Shelf
CREAM	Cognitive Reliability and Error Analysis Model
CxP	Constellation Program
dB	decibel
DDSM	Directory of Design Support Methods
Decomp.	Decomposition
Defn	Definition
Dev	Development
DoD	Department of Defense
DR	Decommissioning Review
DRM	Design Reference Mission
DRR	Disposal Readiness Review
ECS	Environmental Control System
EEE	Electrical, electronic, and electromechanical
EEGS	Emergency Egress Guidance System
EELS	Emergency Egress Lighting System
EMD	Engineering & Manufacturing and Development
EOS	Emergency Oxygen System
EPA	Environmental Protection Agency
ERG	Employee Resource Group
ESD	Exploration Systems Development
ETA	Engineering Technical Authority

ACRONYMS AND ABBREVIATIONS

EVA	Extravehicular Activity
Fab	Fabrication
FAA-HF-STD	Federal Aviation Administration Human Factors Standard
FOIA	Freedom of Information Act
FRR	Flight Readiness Review
GE	General Electric
GSE	Ground Support Equipment
HCD	Human-Centered Design
HFE	Human Factors Engineering
HIDH	Human Integration Design Handbook
HIDP	Human Integration Design Processes
HITL	Human-in-the-loop
HMI	Human Machine Interface
HMTA	Health and Medical Technical Authority
HQ	Headquarters
HSF	Human Space Flight
HSI	Human Systems Integration
HSIG	Human Systems Integration Group
HSIP	Human Systems Integration Plan
HSIPG	Human Systems Integration Practitioner's Guide
HSIR	Human Systems Integration Requirements
HSIT	Human Systems Integration Team
I/F	Interface
ICAWS	Integrated caution, advisory, and warning system
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
IPD	Integrated Product Development
IPT	Integrated Product Team
ISO	International Standards Organization
ISSP	International Space Station Program
JSC	Johnson Space Center
KDP	Key Decision Point
KPP	Key Performance Parameter
LCC	Life Cycle Cost
LOC	Loss of Crew
LOM	Loss of Mission
LRU	Line Replacement Unit
LSS	Life Support System
M&S	Maintenance & Supportability
MBSE	Model-Based System Engineering
MCR	Mission Concept Review
MDR	Mission Design Review
MIL-HDBK	Military Handbook

ACRONYMS AND ABBREVIATIONS

MIT	Massachusetts Institute of Technology
MOE	Measure of Effectiveness
MOP	Measure of Performance
MORD	Medical Operations Requirements Document
MPCV	Multi-Purpose Crew Vehicle
MSFC	Marshall Space Flight Center
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
NASA	National Aeronautics and Space Administration
NASA/SP	NASA Special Publication
NASA-STD	NASA Standard
NASA/TP	NASA Technical Publication
NDIA	National Defense Industrial Association
NEN	NASA Engineering Network
NESC	NASA Engineering and Safety Center
NPD	NASA Policy Directive
NPR	NASA Procedural Requirement
NRC	Nuclear Regulatory Commission
O ₂	Oxygen
OBOGS	On-board Oxygen Generating Systems
OBT	On-board Training
OCE	Office of the Chief Engineer
OCHMO	Office of the Chief Health and Medical Officer
ORR	Operational Readiness Review
ORU	Orbital Replacement Unit
OSMA	Office of Safety and Mission Assurance
P/P	Program and/or Project
PDR	Preliminary Design Review
PFAR	Post-flight Assessment Review
PLAR	Post-Launch Assessment Review
PM	Project/Program Manager
PPF	Project Process Flow
PPO ₂	Partial pressure of oxygen
PRR	Production Readiness Review
R&R	Roles and Responsibilities
Reqts	Requirements
RM&S	Reliability, Maintainability & Sustainability
RRAA	Roles, Responsibilities, Accountability and Authority
RTCA	Radio Technical Commission for Aeronautics
S&MA	Safety and Mission Assurance
SAB	Scientific Advisory Board
SAR	System Acceptance Review
SDR	System Design Review

ACRONYMS AND ABBREVIATIONS

SE	Systems Engineering
SE&I	Systems Engineering and Integration
SEE	Systems Engineering Engine
SEHB	Systems Engineering Handbook
SEMP	System Engineering Management Plan
SIG	Systems Integration Group
SIR	System Integration Review
SLS	Space Launch System
SMA	Safety and Mission Assurance
SMA TA	Safety and Mission Assurance Technical Authority
SME	Subject Matter Expert
SRR	System Requirements Review
SSP	Space Station Program
SUS	System Usability Scale
T&E	Test and Evaluation
TA	Task Analysis
TA	Technical Authority
Tech	Technical
THE	Technology-Human-Environment
TLI	Technical Leading Indicator
TLX	Task Load Index
TPM	Technical Performance Measure
TRR	Test Readiness Review
U.S.	United States
UPG	Upper pressure garment
USAF	U.S. Air Force
V&V	Verification and Validation
VSM	Vehicle Systems Management
WG	Working Group

Executive Summary

The NASA/SP-2015-3709, Human Systems Integration (HSI) Practitioner's Guide, also known as the "HSIPG," provides a tool for implementing HSI activities within the NASA systems engineering framework. The HSIPG is written to aid the HSI practitioner engaged in a program or project (P/P), and serves as a knowledge base to allow the practitioner to step into an HSI lead or team member role for NASA missions. Additionally, this HSIPG is written to address the role of HSI in the P/P management and systems engineering communities and aid their understanding of the value added by incorporating good HSI practices into their programs and projects. Through helping to build a community of knowledgeable HSI practitioners, this document also hopes to build advocacy across the Agency for establishing strong, consistent HSI policies and practices.

Human Systems Integration (HSI) has been successfully adopted (and adapted) by several federal agencies—most notably the U.S. Department of Defense (DoD) and the Nuclear Regulatory Commission (NRC)—as a methodology for reducing system life cycle costs (LCCs). These cost savings manifest themselves due to reductions in required numbers of personnel, the practice of human-centered design, decreased reliance on specialized skills for operations, shortened training time, efficient logistics and maintenance, and fewer safety-related risks and mishaps due to unintended human/system interactions. The HSI process for NASA establishes how cost savings and mission success can be realized through systems engineering.

Every program or project has unique attributes. This HSIPG is not intended to provide one-size-fits-all recommendations for HSI implementation. Rather, HSI processes should be tailored to the size, scope, and goals of individual situations. The instructions and processes identified here are best used as a starting point for implementing human-centered system concepts and designs across programs and projects of varying types, including manned and unmanned, human spaceflight, aviation, robotics, and environmental science missions. The practitioner using this guide should have expertise in Systems Engineering or other disciplines involved in producing systems with anticipated human interactions. (See section 1.6 of this guide for further discussion on HSI discipline domains.)

The HSIPG provides an "HSI layer" to the NASA Systems Engineering Engine (SEE), detailed in NASA Procedural Requirement (NPR) 7123.1B, NASA Systems Engineering Processes and Requirements, and further explained in NASA/SP-2007-6105, Systems Engineering Handbook (see HSIPG Table 2.2-1, NASA Documents with HSI Content, for specific references and document versions).

1.0 INTRODUCTION TO NASA HUMAN SYSTEMS INTEGRATION

NASA systems are designed to fulfill mission goals and scientific objectives by addressing various stakeholder needs and constraints. HSI is a system engineering discipline that applies knowledge of human capabilities and limitations throughout the design, implementation, and operation of hardware and software. *The Human* in HSI refers to all personnel involved with a given system, including users, operators, maintainers, assemblers, ground support personnel, logistics suppliers, personnel trainers. HSI embraces the concept of *The Human* as a sub-system on par with the hardware and software sub-systems.

The HSI discipline includes a range of managerial and technical domains and specialties—e.g., systems engineers, program managers, NASA institutional support offices, human factors engineers, safety and reliability analysts, psychologists, medical professionals, logistics and maintenance expertise. HSI domains collectively define (a) how human capabilities or limitations impact the hardware and software of any given system, in terms of its design, effectiveness, operation, support and the associated cost and affordability of these components, and (b) how the system hardware, software, and environment impact human performance. Total system performance is a measurable outcome of the effectiveness of the integrated interaction of hardware, software, and human elements. Essential engineering expertise areas change as the systems engineering (SE) lifecycle progresses. For this reason, these roles and responsibilities must be identified within the Human Systems Integration Plan at the outset of a project, either as a standalone document or as a part of a program's or project's (P/P's) System Engineering Management Plan (SEMP).

1.1 Guide Purpose

The purpose of the NASA/SP-2015-3709, Human Systems Integration (HSI) Practitioner's Guide, also known as the HSIPG, is to enable incorporation of Agency HSI policies and processes into development and deployment of NASA systems. The HSIPG is intended to serve as a training and support aid for NASA HSI practitioners and their team members. The HSIPG is written to aid the HSI practitioner engaged in a P/P, and serves as a knowledge base to allow the practitioner to step into an HSI lead or team member role for NASA missions. Additionally, this guide should be shared with others in the P/P management and SE communities as an aide to their understanding the value added by incorporating good HSI practices into their endeavors.

Specific aims of this guide are to define HSI, to illustrate the value of HSI in programmatic decisions, to demonstrate how HSI fits into the NASA SE process, to provide examples of HSI contributions to reductions in human error and life cycle cost (LCC), and to provide helpful information on HSI resources within the NASA community.

The Human Systems Integration Plan (HSIP) is a recommended deliverable defined in NASA Procedural Requirement (NPR) 7123.1B, NASA Systems Engineering Processes and Requirements, Appendix G: Life-cycle and Technical Review Entrance and Success Criteria, and in the supporting Systems Engineering Handbook (SEHB) (see HSIPG Table 2.2-1, NASA Documents with HSI Content, for specific references and document versions). This guide supports creating the HSI Plan.

Every P/P has unique attributes. This guide is not intended to provide one-size-fits-all recommendations for HSI implementation. Rather, HSI processes should be tailored to the size, scope, and goals of individual situations. The instructions and processes identified here are best used as a starting point for implementing human-centered system concepts and designs across programs and projects of varying types, including manned and unmanned, human spaceflight, aviation, robotics, and environmental science missions. The practitioner using this guide should have expertise in SE or other disciplines involved in producing systems with anticipated human interactions. (See section 1.6 of this guide for further discussion on HSI discipline domains.)

Since HSI is an emerging requirement in NASA programmatic and management policies and practices, it is recommended that this guide be reviewed and updated when appropriate to capture evolving developments in the pathway towards a recognized, documented NASA approach to HSI.

1.2 How to Use this Guide

This guide is written to support multiple use scenarios, as shown below, following Table 1.2-1, Chapter Purpose. The guidance in the use case scenarios are not meant to be prescriptive or restrictive, but to provide a mechanism to categorize a reader's background and provide the right HSI material to support an aspiring practitioner.

Chapter 3 provides the “step-by-step” guidance for each phase of the SE life cycle. The tables in each section of Chapter 3 are a streamlined representation of the complex, recursive, iterative, and tailorable Systems Engineering Engine (SEE) processes. The reader is advised to acquire a solid grasp of the SEE processes, by study or through training, in order to be able to successfully apply HSI.

Table 1.2-1 Chapter Purpose

Chapter	Short Title	Purpose
1	Introduction to HSI	<p>“Why HSI”</p> <ul style="list-style-type: none"> • Background and History • Key Concepts • HSI Domains
2	Implementing HSI	<p>“Who”</p> <ul style="list-style-type: none"> • Authority hierarchy • NASA HSI Documents • Collaboration
3	HSI in NASA SEE	<p>“When” and “What”</p> <ul style="list-style-type: none"> • A Phase-by-Phase HSI Overlay to NASA SEE • Product maturity by Phase
4	Planning and Execution	<p>“How”</p> <ul style="list-style-type: none"> • Getting Organized • Tailoring for Program/Project Size • Planning for HSI • Key Skills for the HSI Practitioner

Chapter	Short Title	Purpose
App. A	HSI Plan Outline	Annotated HSI Plan outline to aid HSI practitioner development of HSI Plan
App. B	HSI Planning Checklist	Sample of checklist to aid practitioner in assessing scope of HSI effort during early lifecycle phases
App. C	HSI Implementation Experiences	HSI implementation examples with positive/negative lessons learned and HSI ideal state
App. D	References	List of HSI information from NASA, Industry, DoD, and other sources

1.2.1 HSIPG Use Cases

General: Regardless of background, all readers should understand the four Key Concepts of HSI in section 1.4, the HSI process approach in section 1.5, and be familiar with the HSI Domains in section 1.6. Also, review the annotated HSI Plan Outline in Appendix A. If supporting an existing Program or Project, review the SEMP and/or HSI Plan, if they exist.

Use Case 1: I already know the fundamentals of the SEE in the SEHB, but where do I get HSI-specific Skills and Guidance?

Answer: Start with HSIPG sections 4.5 and 4.6 for picking up “how-to” and key practices. Then use HSIPG Chapter 3 to provide the “HSI layer” to the NASA life cycle phases and SEE. For domain-specific knowledge (e.g., Human Factors Engineering [HFE]), utilize the NASA Engineering Network (NEN) site for best practices and resources. Many HFE resources are also listed in HSIPG Chapter 5.

Use Case 2: I already know HFE, so how do I expand my knowledge to include HSI and the SEE?

Answer: Start with HSIPG Chapter 3 to learn more about the NASA SEE. For further study, refer to fundamentals and life cycle sections of the SEHB. Then read HSIPG Chapter 4.

Use Case 3: I was just assigned as an HSI practitioner for a project. Where do I start?

Answer: It is recommended that HSI Practitioners read the entire guide. A person who is the designated HSI practitioner should be well informed with the entire content of the HSIPG and the resources that are referenced. Having said that, sometimes a practitioner will have to “jump in” to an already up and running project. If that is the case, then it is recommended to start with the current life cycle phase discussion in the appropriate section of Chapter 3, for near-term activities. And then refer to section 4.4, which describes details on most activities a practitioner will help conduct for the P/P, such as building a team and writing an HSI plan. Eventually, a gap analysis may need to be performed to assess if any activities/products were “skipped over” and need to be performed/developed.

HSIPG section 4.2 on tailoring to P/P size will be of particular interest, which will also lead you to the HSI Implementation Planning Checklist in HSIPG Appendix B. From there you can begin to organize the HSI team, budget, and expectations.

Use Case 4: I am a project manager and I need to be in compliance with NPR 7123.1B, which now includes performing HSI. I do not have much time, so what do I really need to know?

Answer: Review HSIPG Chapters 1-3 plus section 4.2. And then find yourself an HSI Practitioner.

1.3 History of HSI

Systems have become increasingly complex, often due to the enormous capabilities and advances of micro-circuitry and digital firmware/software. Early and careful consideration of the capabilities and limitations of human performance and behavior when interacting with such complexity has become essential to planning and designing for total system outcome and performance. Hardware and software systems enable humans to perform advanced mission tasks and objectives in extreme and potentially lethal environments. Systems can be designed that to require high levels of human specialization and training or that to accommodate a broad population of human capabilities. The goal of HSI is to ensure that the human/system integration is carefully considered and planned from the outset of any program or project.

The DoD was the first U.S. government agency to identify the need for better design processes for early and thorough consideration of the human element in systems design since they were facing rapid ubiquitous rates of escalation in life cycle system costs due to unanticipated personnel training costs, user interface re-designs, logistics and maintenance expenses, system down time, and repair costs necessary to keep systems operational. Since most cost escalations were due to personnel time and expenditures, it became clear that better design practices for inclusion of the human elements required to develop, deploy, and operate a system needed to become standard in life cycle SE and P/P management. Synergistic interaction between a system and its human elements is key to attaining expected total system performance outcomes and to minimizing total ownership costs. Therefore, to realize the full and intended potential that complex systems offer, the DoD in 2003 mandated that a “total system approach” must apply HSI to all developments “to optimize total system performance (hardware, software, and human), operational effectiveness, and suitability, survivability, safety, and affordability” [DoD Directive 5000.01, The Defense Acquisition System, Enclosure (requirement 1.29)].

Development activities must apply rigorous application of systemic approaches to HSI to ensure the total impact of human capabilities and limitations throughout a system's life cycle are addressed in every aspect of system acquisition. The current DoD Instruction 5000.02, Operation of the Defense Acquisition System, Enclosure 7 (section 2), states that:

[The goal of HSI is] "to optimize total system performance and total ownership costs, while ensuring that the system is designed, operated, and maintained to effectively provide the user with the ability to complete their mission."

In practice, this means that the human element in acquisition programs is given equal importance to hardware and software.

NASA has a history of considering human health and performance in spacecraft and mission design, particularly in human space flight mission planning and design. Human space flight research has been conducted since the early 1960s with incremental advancements in human-rated missions and simulators. In the 1970s and 1980s, NASA advanced aviation safety and matured concepts in crew resource management. The 1990s to present day have witnessed NASA advancements in research and automation, system monitoring, information presentation, and information sharing between systems and humans. With NASA's vision of exploration beyond low-Earth orbit, advanced systems are needed that support extended human habitation and autonomy. Such challenges present new opportunities to deploy and employ HSI practices.

NASA, unlike the DoD, did not have a formal acquisition mandate to include HSI activities in programs and projects, or to include HSI deliverables in the procurement process until 2013 (see below). However, NASA does have a rich heritage of concern for and protection of their space flight crews, and as a result has considered human health and performance in spacecraft and mission design for many years. In addition, in 2012 NASA updated NPR 8705.2B, Human-Rating Requirements for Space Systems (w/change 4 dated 8/21/2012), a procedural requirements document intended to ensure the protection and safety of crewmembers and passengers on NASA space missions. The Human-Rating Requirements define and implement processes, procedures, and requirements necessary to produce human-rated space systems, and define a human-rating certification path for the Program Managers (PMs) and their teams to follow in conjunction with select traditional program management milestones.

In 2015, an updated version of NASA-STD-3001, NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health, was released that included a new requirement for Human-Centered Design:

3.5 Human-Centered Design Process [V2 3005]

*Each human space flight program **shall** establish and execute a human-centered design process that includes the following at a minimum:*

- a. Concepts of operation and scenario development*
- b. Task analyses*
- c. Function allocation between humans and systems*
- d. Allocation of roles and responsibilities among humans*

e. Iterative conceptual design and prototyping

f. Empirical testing, e.g., human-in-the-loop, testing with representative population, or model-based assessment of human-system performance

g. In-situ monitoring of human-system performance during flight.

Rationale: Human-centered design is a performance-based approach that focuses on making a design usable by the human throughout the system's life cycle. (See ISO 13407, Human-centered design processes for interactive systems). It is characterized by early and frequent user involvement, performance assessment, and an iterative design-test-redesign process.

A typical human-centered design process is negotiated during the implementation process and documented in a human factors engineering control plan, where each of the above process steps results in at least one documented deliverable. Effective human-centered design starts with a clear definition of human activities, which flows down from the concept of operations and anticipated scenarios, to more specific analyses of tasks and to even more specific questions of allocation of roles and responsibilities between the human and systems (where the term "systems" refers to machines or automated systems). Iterative design is a key component of this process, by which concepts are continually refined. Next, more rigorous evaluation of designs is required, by computational human modeling, empirical methods, or a blend of the two. Empirical methods include laboratory studies and human-in-the-loop simulation testing. Finally, real-time measurements of system performance are needed during flight to generate lessons learned. More information about methods and techniques can be found in chapter 3, General, of the HIDH.

Inclusion of this requirement for all human space flight programs was a significant step forward in capturing and documenting a NASA approach to HSI. Note, however, that this only currently applies to human space flight programs, but not to other NASA programs such as aviation and unmanned space exploration. Nonetheless, a human-centered design (HCD) approach to system acquisition and development is a critical concept in HSI. More information on methods and techniques in HCD can be found in NASA/SP-2010-3407R1, Human Integration Design Handbook (HIDH), Chapter 3, General, a companion document to NASA-STD-3001.

In 2012, two groups of NASA personnel interested in HSI were formed to spread and promote information on the topic and to work toward a NASA-specific implementation of HSI. A multi-Center HSI Steering Committee was chartered under the auspices of the Office of the Chief Engineer (OCE). The charter for the OCE HSI Steering Committee includes signature membership of 10 NASA Centers. At the Johnson Space Center (JSC), an HSI Employee Resource Group (ERG) was formed to socialize, inform, and promote HSI across JSC technical directorates. Members of the HSI ERG worked with JSC's Systems Engineering Forum to form an HSI Splinter to the Forum to initiate efforts to change NASA's SE documentation to be more inclusive of HSI and the human element.

In 2013, NPR 7123.1B was updated to Revision B, in which a definition of HSI was for the first time formally captured in NASA documentation:

Human Systems Integration: An interdisciplinary and comprehensive management and technical process that focuses on the integration of human considerations into the system acquisition and development processes to enhance human system design, reduce life-cycle ownership cost, and optimize total system performance. Human system domain design activities associated with manpower, personnel, training, human factors engineering, safety, health, habitability, and survivability are considered concurrently and integrated with all other systems engineering design activities.

NPR 7123.1B also includes a guideline that all NASA programs and projects generate an HSI Plan that captures the implementation of HSI on the P/P. Appendix G of the NPR provides recommended milestones during the P/P life cycle at which the HSI Plan is updated with new information as the P/P matures.

In 2014 NASA released NASA/TP-2014-218556, Human Integration Design Processes (HIDP), which captures NASA human engineering and HSI lessons learned that are not adequately addressed by standards and requirements alone—i.e., they are complex, iterative processes such as determining the appropriate net habitable volume of a human space flight spacecraft for a given crew size, mission scope, and mission duration. As of 2015, NASA/SP-2007-6105—a companion to NPR 7123.1B—is being revised. The update will include significant new information on HSI and on integrating the human element into NASA SE processes. See HSIPG Table 2.2-1, NASA Documents with HSI Content, for specific references and document versions of the SEHB.

1.4 Key Concepts of HSI

Four key concepts define an effective HSI effort.

- 1) The system comprises hardware, software, and human elements needed to operate and maintain the system within an environment. As demonstrated in several HSI case studies in Appendix C, the human element is critical to the overall performance, effectiveness, and efficiency of the total system. The initial paragraph of NPR 7123.1B states that, “This systems [engineering] approach is applied to all elements of a system (i.e., hardware, software, human system integration [sic]) and all hierarchical levels of a system over the complete project life cycle.” [Editor’s note: typo; “system integration” should not appear in this quote.]
- 2) Human interactions that need to be considered in P/P management, SE, and HSI include all personnel that interface with a system in the expected environment and at any and all phases of the system’s life cycle—i.e., the end users (pilots, crewmembers), maintainers, ground controllers, logistics personnel, sustaining engineers, etc.
- 3) Successful HSI depends upon integration and collaboration of multiple domains. Prior to the concept of HSI, separate human-centered domains had to interact with the P/P management structures as independent disciplines due to the lack of a coordinated approach to including the human element in system design and engineering. Proper

implementation of HSI helps all human-centered domains have a more assured, coordinated voice in system design and engineering. In addition, having HSI coordinators helps the P/P managers since it is expected that the HSI team lead will resolve or mitigate conflicting inputs among human systems subject matter experts before the P/P management needs to engage. Via internal integration, HSI domain interests can better participate in P/P trade studies and design collaboration.

- 4) HSI must be considered and established in P/P planning early in system development and acquisition—i.e., in the early concept and design phases of NASA SE—and applied iteratively throughout the development life cycle from pre-Phase A through to Phase F (refer to Figure 1.4-1, NASA Life Cycle Phases). Early application of HSI provides the best opportunity to maximize LCC efficiency and total system performance. HSI requirements and goals must be developed in phase with system capability-based requirements. HSI requirements will drive HSI metrics and embed HSI goals within the system design. After a system is designed, implementation of HSI oversight or workarounds due to the lack of HSI during design can be very expensive.

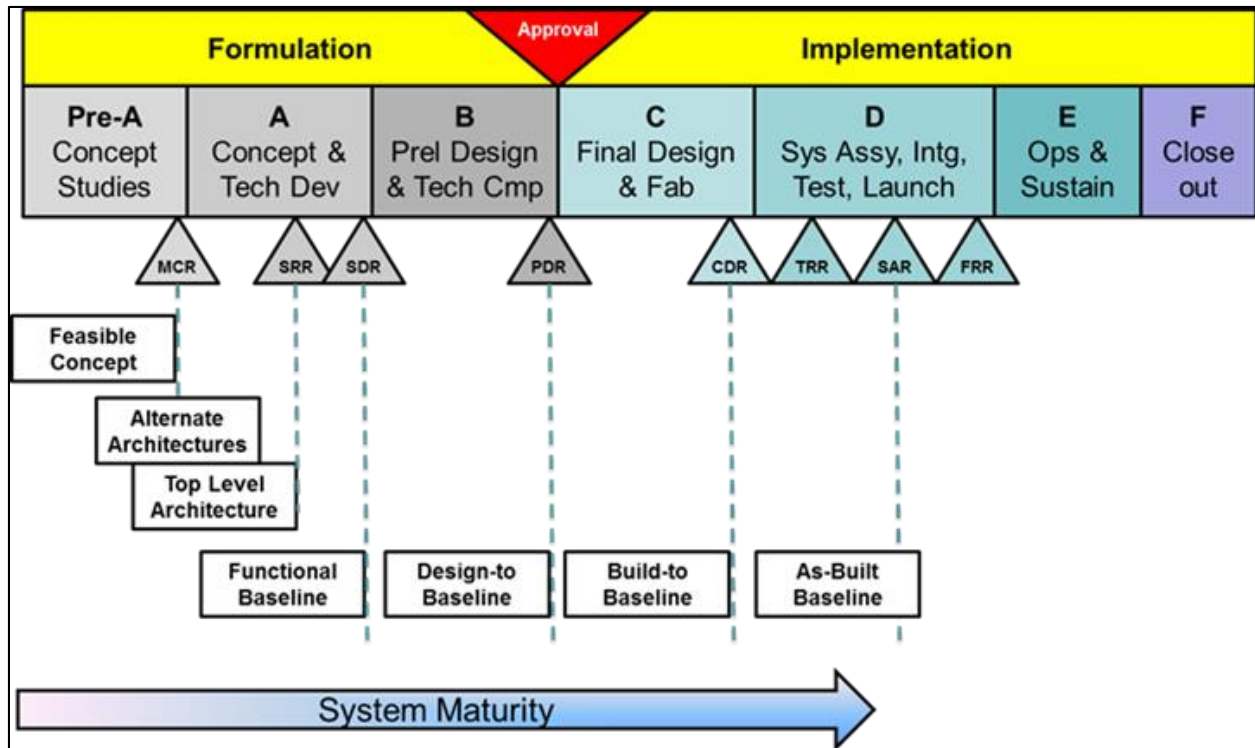


Figure 1.4-1 NASA Life Cycle Phases

Expanding on this last point, as noted earlier, the DoD made HSI mandatory when faced with alarming, unanticipated cost escalation in deploying new weapon systems. Much of the unexpected cost growth was due to personnel costs in systems' operations phase—i.e., it took more people and more advanced skills to operate, maintain, and logistically support systems than was planned. Faced with the awareness of cost growth in the human elements needed to make and keep systems operational, HSI was seen as a methodology to focus on systems' full LCCs—conception through operations—starting at the outset of new programs and projects. Figure 1.4-2, based on a figure from the INCOSE Systems Engineering Handbook (2007), shows that LCC of a program or project are “locked in” early in programs or projects.

Although this early pre-determination of systems' LCC may apply to any element of systems' design whose consideration is neglected in the early P/P, it is particularly noteworthy for HSI, since hardware and software system designers quite often focus on technology development to the detriment of considering the human elements of a system. A discussion of the LCC effects of HSI is contained in section 4.4.9 of this HSIPG .

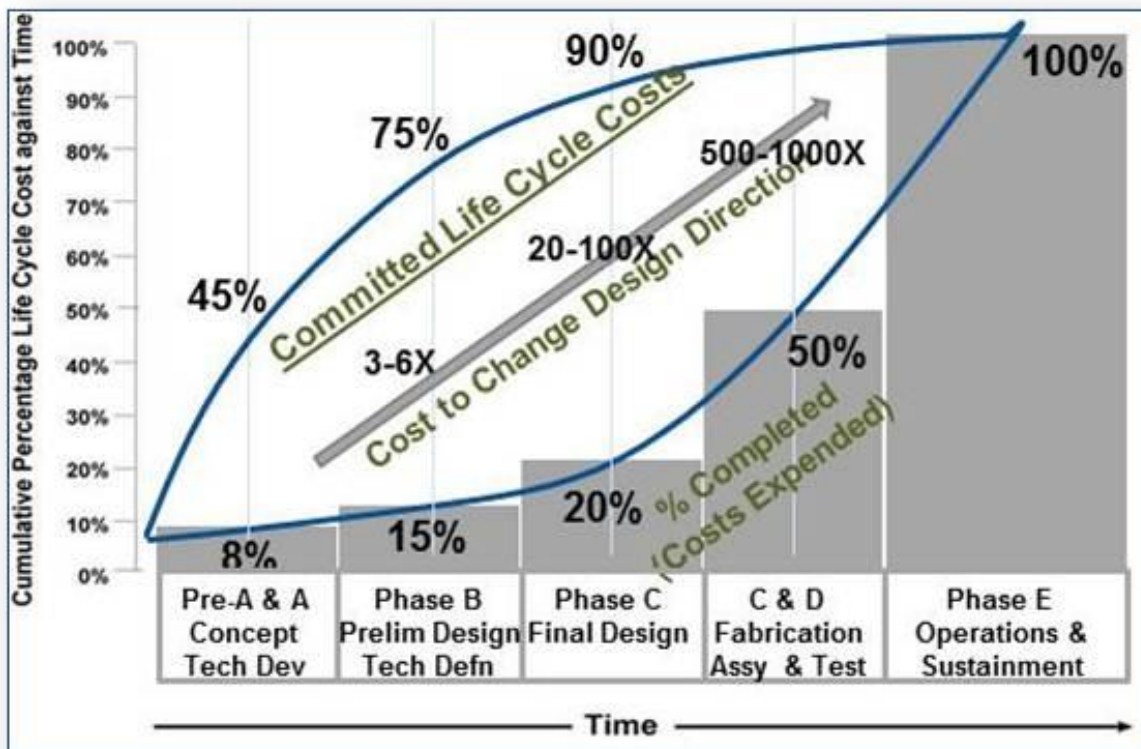


Figure 1.4-2 Life Cycle Cost with Overlay Showing “Locked-in” Costs

1.5 The NASA HSI Process Approach

Ideally, NASA programs and projects treat HSI as an integral part of the standard SE process such that when the SEE “runs”—i.e., during execution of the SE process—HSI work is performed. In this document, you will encounter a tight synchronization between HSI process and the NASA SEE processes. The steps to execute HSI processes are in lock-step with the NASA SEE processes. The NASA P/P Life Cycle from an HSI perspective is provided in Chapter 3 of this guide.

The NASA approach of identifying HSI as a cross-cutting process provides HSI structure to the SEE, while still allowing for tailoring of HSI to the mission of a P/P. The first benefit of this approach is that a system engineer can readily learn to be an HSI practitioner. Similarly, by performing HSI, human-centered design practitioners learn SE best practices and facilitate execution of SEE processes.

The second benefit of this approach is directly to the P/P stakeholders—i.e., to ensure that the original operational vision is fulfilled. The HSI practitioner can provide ongoing P/P objectivity through continually insisting on validation of questions such as, “Are we building the system originally envisioned?” or “Does this system design solve the stakeholders’ challenge and fulfill the stakeholders’ needs?”

The third benefit is the immediate applicability of HSI practices to SE workflow. By integrating HSI with the SEE, HSI becomes another best practice for systems engineers rather than something that “somebody else” performs.

1.6 HSI Domains

HSI incorporates functional areas, referred to as domains. . NASA HSI domains are listed in Table 1.6-1. HSI personnel with integrated domain oversight implement HSI processes and practices and integrate HSI domain involvement throughout the NASA SE life cycle. Overall HSI domain integration oversight is essential to effective HSI implementation. While there may be overlap among those responsible for overall HSI domain integration and specific domain expertise, the parties responsible for providing consolidated HSI input rely on discipline experts in the HSI domains—i.e., they do not replace them. Functional implementation of HSI is based on regular and frequent communication, coordination, and integration across the HSI domains providing human-systems expertise.

As Figure 1.6-1 illustrates, each HSI domain has the potential to affect and interact with the other domains, making it critical to execute an integrated discipline approach. Human Factors Engineering (HFE) is the central domain in that it is responsible for characterizing human capabilities and constraints and for applying knowledge of these to engineered hardware/software engineering systems’ design. Because of their direct interaction with systems’ design, recommendations by HFE discipline experts can have a strong influence on mission success and operations costs, working collaboratively with the principles, goals, and metrics of all the other domains.

Table 1.6-1 NASA HSI Domains

Domain	Definition	Examples of Expertise
Human Factors Engineering (HFE)	Designing hardware and software to optimize human well-being and overall system safety, performance, and operability by designing with an emphasis on human capabilities and limitations as they impact and are impacted by system design across mission environments and conditions (nominal, contingency, and emergency) to support robust integration of all humans interacting with a system throughout its life cycle. HFE solutions are guided by three principles: system demands shall be compatible with human capabilities and limitations; systems shall enable the utilization of human capabilities in non-routine and unpredicted situations; and systems shall tolerate and recover from human errors.	Task analysis, human performance measures (workload, usability, situation awareness), HFE Design (anthropometry and biomechanics, crew functions, habitat architecture), HITL Evaluation, Human Error Analysis, Human-system Interface, Systems Design, and HFE Analysis
Operations Resources	The considerations and resources required for operations planning and execution. This includes operability and human effectiveness for flight and ground crews to drive system design and development phases, as well as trades for function allocation, automation, and autonomy.	Operations process design for both ground and flight crew, human/machine resource allocation, Mission Operations, Resource modeling and complexity analysis, Flight Operations, procedure development, crew time, staffing/qualifications analysis
Maintainability and Supportability	Design to simplify maintenance and optimize human resources, spares, consumables, and logistics, which are essential due to limited time, access, and distance for space missions.	In-flight Maintenance and Housekeeping, Ground Maintenance and Assembly, Sustainability and Logistics
Habitability and Environment	External and internal environment considerations for human habitat and exposure to natural environment including factors of living and working conditions necessary to sustain the morale, safety, health, and performance of the user population which directly affect personnel effectiveness.	Environmental Health, Radiation Health, Toxicology, Nutrition, Acoustics, Architecture Crew Health and Countermeasures, EVA Physiology, Medical Concerns, Lighting
Safety	Safety factors ensure the execution of mission activities with minimal risk to personnel. Mission success includes returning the crew following completion of mission objectives and maintaining the safety of ground personnel.	Safety analysis, Reliability, Quality Assurance, factors of survivability, human rating analysis, hazard analysis
Training	Design training program to simplify the resources that are required to provide personnel with requisite knowledge, skills, and abilities to properly operate, maintain, and support the system.	Instructional Design, Training Facility Development, On-board Training (OBT)

Though not shown in Figure 1.6-1, survivability is part of the HFE, Safety, and Habitability and Environment domain analysis.

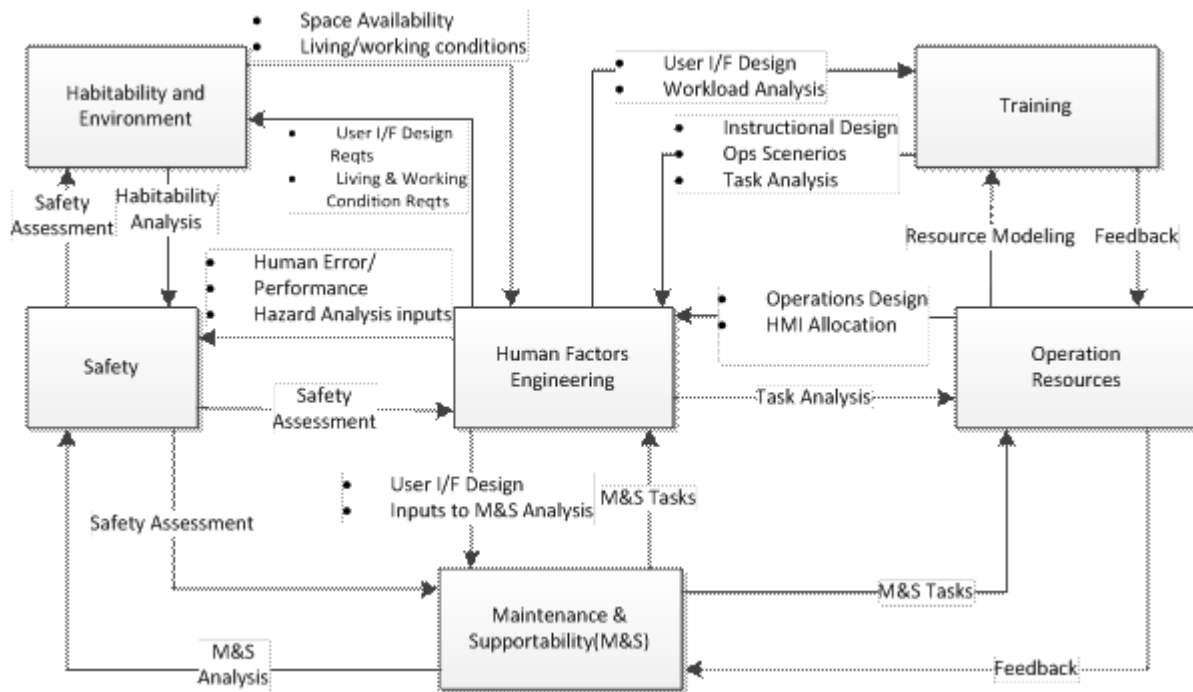


Figure 1.6-1 HSI Domain Interaction

Note that the AFD-090121-054, Air Force Human Systems Integration Handbook: Planning and Execution of Human Systems Integration (2008), identifies the following nine domains: Manpower, Personnel, Training, HFE, Environment, Safety, Occupational Health, Survivability, and Habitability. The long-established DoD HSI domain categories were assessed and customized by the NASA OCE HSI Steering Committee to establish the set of domains for NASA HSI implementation. The NASA HSI domains are less focused on the large work force and diverse skill sets required for DoD mission objectives and more focused on habitability, system safety, reliability, and usability concerns. HFE is a significant domain for both DoD and NASA HSI processes.

1.7 Distinguishing HSI, HCD, and HFE as Systems Engineering Elements

The terms HSI, HCD, and HFE are all used in concert within this document. HSI is defined by NASA in NPR 7123.1B and is further described with its technical domains in Table 1.6-1 and in the early sections of this guide.

HFE is defined in Table 1.6-1 as one of the HSI domains.

HCD is defined as an approach to interactive system development that focuses on making systems usable by ensuring that the needs, abilities, and limitations of the human user are met. HCD is a multi-disciplinary activity that involves a range of skills and stakeholders that collaborate on design. Most importantly, HCD is applied through an iterative approach that uses data gathered from frequent evaluations with users to inform system design. (Refer to NASA/TP-2014-218556.)

In summary, as an inherent part of the NASA SE process, HSI applies and integrates multiple domains including HFE, and it employs the HCD approach for system design.

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2.0 IMPLEMENTING HUMAN SYSTEMS INTEGRATION

2.1 NASA-HSI Authority

Within the organization of NASA, there are programmatic authorities (mission directorates) and institutional authorities (cross-cutting technical offices). Control boards are the method for institutional and programmatic authorities to reach agreements on specific P/P issues.

2.1.1 Programmatic Authorities

NASA mission directorates provide programmatic authority and they create P/P to carry out their initiatives. These P/P fund NASA Center institutional organizations (e.g., Engineering, Safety and Mission Assurance [S&MA], Human Health and Performance [HH&P], Mission Operations) to staff the P/P technical offices and teams. These P/P-funded technical personnel include program managers, systems engineers, and infrastructures that often derive from Center institutional resources but that may become P/P direct hires and resources. These P/P personnel execute the implementation of Agency P/P directives such as NPR 7120.5E, NASA Space Flight Program and Project Management Requirements w/Changes 1-13. Typically, P/P funds are also deployed to engage subject matter experts (SMEs) in the specific areas necessary to execute the P/P. Thus, program HSI work is arranged and managed by P/P-funded personnel (NASA civil servants and often the program's prime contractor), in coordination with the cognizant NASA Institutional Technical Authorities. P/P-funded SME personnel are the primary resources by which HSI work is accomplished to execute the necessary HSI processes and products for the program or project. The involvement of NASA SMEs generates technical insight into the P/P needed by the Technical Authorities (TAs) to monitor progress.

2.1.2 Institutional Authorities

NASA institutions typically provide the skills (personnel) and resources (facilities, labs, etc.) to execute HSI when funded to do so by a particular program or project. Additionally, NASA institutions have a responsibility to provide necessary functions that are separate from those of programmatic authorities. Related to implementation of HSI, one of their key functions is that of technical authority. The three NASA TAs are:

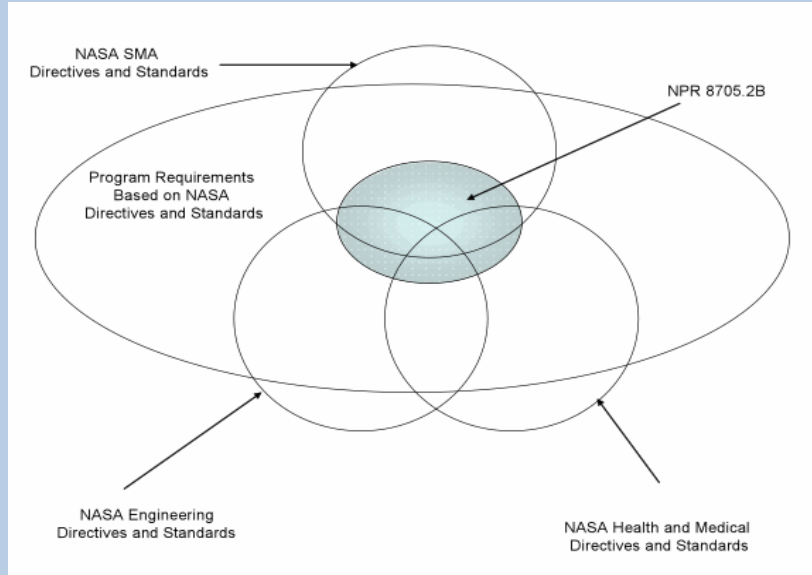
- 1) The Engineering Technical Authority (ETA) is a function of the Agency's OCE. ETA is delegated from the Agency's Chief Engineer to Center Directors and further delegated within the centers. Refer to NPR 7120.5E for details of the ETA. The principal ETA documents currently supporting HSI are NPR 7123.1B and the accompanying SEHB (see document references in table 2.2-1).
- 2) The Safety and Mission Assurance Technical Authority (SMA TA) is a function of the Office of Safety and Mission Assurance (OSMA). SMA TA is delegated from the Agency's Chief of S&MA to Center Directors and further delegated within the centers. Refer to NPR 7120.5E for details of the SMA TA. The OSMA manages NPR 8705.2B, which specifies many processes related to good HSI practice—e.g., requiring application of NASA-STD-3001 to human-rated P/P. NPR 8705.2B also calls for establishing a formal HSI team for human space flight P/Ps that results in human-rated space flight systems. Pending updates to NPR 8705.2B will add significant new information on HSI Team roles and responsibilities.

- 3) The Health and Medical Technical Authority (HMTA) is a function of the Office of the Chief Health and Medical Officer (OCHMO). The OCHMO promulgates the Agency's human health and performance technical standards that must be met by programs and projects. Refer to NPR 7120.11, NASA Health and Medical Technical Authority (HMTA) Implementation, for details of the HMTA. HMTA is delegated from the Administrator to the Chief Health and Medical Officer (CHMO). HMTA is further delegated to center-level Chief Medical Officers (CMOs) at specific NASA centers. Each center CMO is the HMTA for P/P and programs at that center. At centers without an HMTA presence, the ETA and SMA TA have agreed to provide an insight function to alert the OCHMO of human systems issues within programs and/or projects at those centers. (Refer to NPR 7120.5E and NPR 7120.11 for details of this process.) Uniquely, the HMTA for all human space flight programs and projects at all centers is delegated to the JSC CMO. The JSC CMO designates individuals as HMTA Delegates to each human space flight P/P. These HMTA Delegates are the authorized individual points of contact to implement the HMTA role for the P/P. To date, on major human space flight programs they have also typically been assigned as the program-funded HSI lead responsible party (see section 2.1.1, Programmatic Authorities) because of the close relationship between accomplishing HSI work and meeting the human health and performance technical standards applied to the P/P.

The primary HMTA document related to the design and development phases of human space flight HSI is NASA-STD-3001, Space Flight Human-System Standard, Volume 1A, Crew Health, and Volume 2A, Human Factors, Habitability, and Environmental Health. The HMTA has the overall authority to maintain NASA-STD-3001, though all three NASA TAs must approve modifications to Volume 2. Additionally, HMTA personnel maintain NASA/SP-2010-3407, that accompanies NASA-STD-3001, NASA/TP-2014-218556, and this HSIPG, although this document is also coordinated through the Agency OCE HSI Steering Committee.

Currently, NASA has not yet determined the method by which HSI will be integrated with the TA governance model. However, similar to where Human Rating reaches, HSI domains span each of the 3 TA domain areas, as shown in the figure in the "blue box" below.

Technical Authority Domain Areas (from NPR 8705.2B)



2.1.3 Control Boards

Control boards coordinate communication between institutional and programmatic authorities to reach agreements on specific program or project issues. The NASA Institutional TAs and the P/P-assigned HSI responsible lead participate in management control boards within a specific program or project. This provides the necessary and unique HSI technical input to P/P management to ensure that HSI is effectively accomplished and that the Agency's institutional technical requirements are met throughout the P/P life cycle. For large, complex programs, there may be multi-level representation at control boards. For example, in NASA's Exploration Systems Development (ESD) enterprise, element-level, vehicle-level, and program-level boards control specific technical content of the system under development, while cross-program control boards enable the highest levels of HSI that span across all the ESD programs.

2.2 HSI in the NASA Program Management Structure

NASA programs and projects are initiated and implemented to accomplish scientific or exploration goals that generally require a collection of mutually supporting projects. Programs integrate and manage these projects over time and provide ongoing support to enabling systems, activities, methods, technology developments, and feedback to projects and stakeholders.

Programs and Projects – Definitions

- a. Program—a strategic investment by a Mission Directorate or Mission Support Office that has a defined architecture and/or technical approach, requirements, funding level, and a management structure that initiates and directs one or more projects. A program implements a strategic direction that the Agency has identified as needed to accomplish Agency goals and objectives.
- b. Project—a specific investment identified in a Program Plan having defined requirements, a life-cycle cost, a beginning, and an end. A project also has a management structure and may have interfaces to other projects, agencies, and international partners. A project yields new or revised products that directly address NASA's strategic goals.

2.2.1 NASA Program Management and Systems Engineering Requirements

NPR 7120.5E establishes the requirements by which NASA formulates and implements space flight programs and projects, consistent with the governance model contained in NASA Policy Directive (NPD) 1000.0B, NASA Governance and Strategic Management Handbook.

Because the goals of programs vary significantly, different program implementation strategies are required, ranging from very simple to very complex. NPR 7120.5E allows for flexibility, but regardless of the structure of a program or project, NPR 7120.5E applies to the full scope of the program or project and all activities under it. Specific NPR 7120.5E requirements are flowed down to these activities to the extent necessary for the P/P to ensure compliance and mission success. Some P/P may be governed by NPR 7120.7, NASA Information Technology and Institutional Infrastructure Program and Project Management Requirements, and NPR 7120.8, NASA Research and Technology Program and Project Management Requirements (w/change 3 dated 4/18/13).

Systems engineering at NASA requires the application of a systematic, disciplined engineering approach that is quantifiable, recursive, iterative, and repeatable for the development, operation, maintenance, and disposal of systems integrated throughout the life cycle of a P/P. The emphasis of SE is on safely achieving stakeholder functional, physical, and operational performance requirements in the intended use environments over the system's planned life within cost and schedule constraints.

NPR 7123.1B establishes common technical processes for implementing NASA products and systems, as directed by NPD 7120.4D, NASA Engineering and Program/Project Management Policy. NPR 7123.1B complements the administration, management, and P/P reviews specified in NPR 7120.5E. NPR 7123.1B is designed to clearly articulate and establish the requirements on the implementing organization for performing SE.

Systems Engineering is a logical systems approach performed by multidisciplinary teams to engineer and integrate NASA's systems to ensure NASA products meet customers' needs. Implementation of this systems approach is intended to enhance NASA's core engineering capabilities while improving safety, mission success, and affordability. This systems approach is applied to all elements of a system (i.e., hardware, software, human) and all hierarchical levels of a system over the complete project life cycle.

Together, NPRs 7120.5E and 7123.1B comprise the primary guidance within the Agency for managing NASA P/P. Many other discipline areas such as health and safety, medical, reliability, maintainability, quality assurance, information technology, security, logistics, and environmental, perform functions during project life-cycle phases that influence or are influenced by the engineering functions performed and need to be fully integrated with the engineering functions. The description of these disciplines and their relationship to the overall management life cycle are defined in other NASA directives and documents. To that end, NPR 7123.1B and the accompanying NASA/SP-2016-6105 Rev 2 contain significant HSI language and references.

2.2.2 Current HSI Documentation and Knowledge Resources for HSI

Several documents contain elements of HSI that support the Agency commitment to include the human as part of the system definition.

Table 2.2-1 NASA Documents with HSI Content

Document	HSI Content
NASA Policy Directives / Procedural Requirements	
NPR 8705.2B, Human-Rating Requirements for Space Systems (w/change 4 dated 8/21/2012)	Processes, procedures, and requirements necessary to produce human-rated space systems that protect the safety of crewmembers and passengers on NASA space missions. For programs that require Human-Rating per this NPR, paragraph 2.3.8 requires the space flight program to form an HSI Team before SRR.
NPR 7123.1B, NASA Systems Engineering Processes and Requirements	Appendix A includes definition of HSI. Appendix G, Life cycle and Technical Review Entrance and Success Criteria, includes an HSI Plan.
NPR 7120.5E, NASA Space Flight Program and Project Management Requirements w/Changes 1-13	Establishes the requirements by which NASA formulates and implements space flight programs and projects, consistent with the governance model contained in NPD 1000.0B, NASA Governance and Strategic Management Handbook. Includes Human Rating requirements.
NPR 7120.11, NASA Health and Medical Technical Authority (HMTA) Implementation	Implements HMTA responsibilities to ensure that Agency health and medical policy, procedural requirements, and standards are addressed in P/P management when applicable and appropriate.
NPR 8900.1A, NASA Health and Medical Requirements for Human Space Exploration	Establishes health and medical requirements for human space flight and the responsibilities for their implementation including health and medical, human performance, habitability, and environmental standards; sponsorship of health-related and clinical research.

Document	HSI Content
NASA Standards Documents and Handbooks	
NASA/SP-2007-6105 Rev1, NASA Systems Engineering Handbook (companion to NPR 7123.1)	Describes SE as it should be applied to the development and implementation of large and small NASA programs and projects. (HSI is explicitly described.)
2016 update to SEHB (companion to NPR 7123.1B)	Includes descriptions of HSI domains, life cycle activities, products, procedures, and practices.
NASA/SP-2007-6105, NASA Systems Engineering Handbook Wall Chart (2007 release)	The SE Handbook wall chart provides an SE view of the project life cycle, including the phase-based SE engine processes.
NASA-STD-3001, NASA Space Flight Human System Standard	OCHMO mandatory standard for NASA human space flight programs. Establishes Agency-wide requirements that minimize health and performance risks for flight crew in human space flight programs. Includes requirement [V2 3005] mandating that human space flight programs establish and execute a human-centered design process.
NASA/SP-2010-3407, Human Integration Design Handbook (HIDH)	Guidance for the crew health, habitability, environment, and human factors design of all NASA human space flight systems.
NASA/TP-2014-218556, Human Integration Design Processes (HIDP)	HSI design processes, including methodologies and best practices that NASA has used to meet human systems and human-rating requirements for developing crewed spacecraft. HIDP content is framed around human-centered design methodologies and processes.
NASA/SP-2014-3705, NASA Space Flight Program and Project Management Handbook (companion to NPR 7120.5E)	Contains context, detail, rationale, and guidance that supplements and enhances the implementation of space flight programs and projects, including an HSI Plan.

In addition to the documents listed in Table 2.2-1, P/P-specific documents may be generated to capture HSI plans, requirements, strategies, etc. For example, the NASA ESD, Multi-Purpose Crew Vehicle (MPCV) 70024, Orion Multi-Purpose Crew Vehicle Human-Systems Integration Requirements, was generated as the program-specific instantiation of NASA-STD-3001 Volume 2. In the International Space Station Program (ISSP), the ISSP-specific instantiation of NASA-STD-3000, Man-Systems Integration Standards (now superseded by NASA-STD-3001) is SSP 50005, International Space Station Flight Crew Integration Standard (NASA-STD-3000/T).

2.3 Collaboration

For the HSI practitioner, collaboration with the PM, Systems Engineer, other P/P team leads, and the overall Program Management and SE infrastructure is the most appropriate and efficient means of ensuring HSI is a core part of every P/P. The goal of working within an agreed upon structure is to enable P/P stakeholders and experts from varied disciplines to consider and address relevant issues and challenges of shared concern and resolve design trades in a rational and cooperative environment. The purpose of working collaboratively is to create an ideal, shared vision that all stakeholders can agree upon, commit to, and finally create action plans to support.

It is essential for the HSI practitioner to collaborate with many elements of the P/P, as well as with relevant institutional organizations where HSI domain SMEs are likely located. HSI is inherently part of the larger P/P's Systems Engineering and Integration (SE&I) infrastructure and has a natural collaborative role with system engineers in defining the P/P's mission and in designing the total system (human + hardware + software) needed to perform the mission. Conceptual design, architectural formulation, function allocation, and operations development are all desired processes and outcomes of early collaboration. HSI collaboration continues through all P/P phases, using NASA SEE processes outlined in NPR 7123.1B and the SEHB.

2.3.1 Integrated Product Team and Working Group Participation

Within a P/P, the HSI practitioner must collaborate with many teams. In Pre-Phase A of the P/P life cycle (see section 4.1 of this guide), the HSI team should play an integral role in defining and refining the system's Concept of Operations (ConOps). Beginning in Phase A and throughout the P/P life cycle, HSI Integrated Product Teams (IPTs) and Working Groups (WGs) participate in design trades and system maturation activities. HSI participation in these teams is critical for providing timely human-centered input to the design process. The HSI practitioner has a close collaborative relationship with (HH&P), S&MA, Engineering, Flight Crew, Ground Support, and Mission Operations teams and their TAs as deemed appropriate. HSI team members participate in the efforts of these other teams via IPTs and WGs and make valuable contributions in order to remain relevant to the program or project and to instill HSI value in all areas.

Refer to section 4.3.2, Organizing the HSI Team, and section 4.4.3, Integration of Subject Matter Expertise for HSI Activities, in this guide for additional details on HSI teaming.

2.3.2 HSI Team Collaboration

Because of the number of human-centered disciplines that the HSI practitioner can and should bring to realization, it is likely that HSI will itself comprise a team, either informally or formally recognized by the program or project, e.g., a P/P-designated HSI IPT. Within the HSI team, extensive interdisciplinary collaboration is required. HSI includes both highly qualified SME personnel who understand details of human characteristics and HSI integrators who know the SE and programmatic methods required to integrate human performance and capacities into the P/P's mission and resulting systems' design, development, and implementation.

A wide range of SME knowledge is integrated by the HSI practitioner in order to create products useful to the P/P. Depending on the nature of the P/P, these SMEs may provide expertise on many specific areas of human health and performance such as those listed in Table 1.6-1.

2.4 HSI and Systems Engineering

Given the level of defined structure for NASA P/P management and SE in NPR 7120.5E and NPR 7123.1B, respectively, the HSI practitioner is advised to learn the details of these top level requirements documents and learn to integrate HSI concerns into their frameworks through collaboration and through developing processes and products that mesh with P/P management and SE. The next chapter of this document describes HSI activities, processes, and products that need to or are appropriate to occur at each step of the NASA SE process. As noted in section 1.3, History of HSI, in 2015 the Agency HSI community worked to insert HSI-specific language into an update to NASA/SP-2007-6105, including identifying HSI products and processes appropriate for every step of SE. This guide compiles and expands on this information in order to provide the HSI practitioner a concise methodology for performing HSI in a P/P environment.

A highly summarized overview of HSI as applied to the NASA SE Process is provided below as a general reference:

- **Concept Development:** Participating early to ensure HSI considerations are included in conceptualization (e.g., function allocation to humans, support analysis of alternatives, flight and ground crew projections, human risk assessment).
- **Requirements Definition:** Being a vital part of the system capabilities and specification definition process. Write clear, concise, and testable HSI-related capabilities and specifications to ensure the human-allocated functions and risks are addressed.
- **Design Development:** Participate in the design process of systems to ensure HSI principles are incorporated into design decisions such that system trade-offs do not marginalize human considerations.
- **Testing and Evaluation:** Conduct verifications of HSI-related system requirements and validation in an operational context to evaluate whether the system adequately facilitates human performance in meeting total mission performance goals.
- **Sustainment/Closeout:** Continue the system support process to ensure HSI concerns are addressed through operational lessons learned, engineering changes, training improvements, etc.

2.5 HSI Team Application of Tools, Models, and Analyses

The HSI Practitioner is responsible for ensuring that appropriate technical models and tools are available to the P/P HSI team in order to accomplish its analytical work. The HSI Practitioner should include these models and tools in the team planning and budgeting, and ensure that the necessary SMEs are engaged to apply the tools. The broad scope of HSI means that many models and tools may be candidates for application on a P/P, but a subset will be selected by the HSI team based on the specific P/P needs, processes, and budget. Results and analysis from use of HSI models and tools can be used in early phase decision making for architecture, design, prototyping, and requirements, and in later phases can support verification and validation (V&V).

There are several key aspects of HSI models and tools:

- Selected based on the needs of P/P and readily available to the HSI team.
- Supportive of the full P/P life cycle including architectural trades, conceptual to detailed design, risk analysis, system performance analysis, HITL testing and demonstration, system development, and mission operations.
- Enables collaboration: the tools produce HSI analytical outputs that are suitable as input to other P/P tools or processes.
- Validated/accredited for their intended uses (per NASA-STD-7009, Standard for Models and Simulations).

Table 2.5-1 lists some examples of analytical tools used for various aspects of HSI. The tools to be applied in a P/P will be documented in the HSI Plan or HSI section of the SEMP.

Table 2.5-1 Representative Examples of HSI Tools

General Type	Specific Examples
Human error analysis	Cognitive Reliability and Error Analysis Model (CREAM)
Workload analysis/evaluation	Bedford evaluation scale, NASA TLX, or other HITL measures
Usability analysis/evaluation	System Usability Scale (SUS) or other HITL measures
Anthropometric analysis	Population analysis, worksite analysis
Task analysis/evaluation	Discrete event simulation
Requirements management	3SL Cradle or other products
Lighting	Radiance modeling
Acoustics	Statistical energy analysis and modeling
Radiation	NASA space cancer risk projection models
Environmental analysis	Water, air, microbial sampling/analysis methods

General Type	Specific Examples
Physiologic analysis	JSC 33124/CTSD-SH-918, 41-Node Transient Metabolic Man Program, Computer Program Documentation, Wissler human thermoregulation analysis -- Decompression sickness Bubble Growth Model
Medical care planning	NASA Integrated Medical Model

3.0 HSI IN THE NASA SYSTEMS ENGINEERING ENGINE

The primary focus of HSI is to recognize and give weight to HSI considerations, identify human performance needs and constraints, and develop HSI requirements. To have impact, these activities must be performed in the early phases of the life cycle. In this section, opportunities to recognize and manage HSI while drafting capability documents during early phases and at major phase key decision points will be discussed. The approach will incorporate both NASA SEE processes and NASA Life Cycle Phases.

3.1 Engine Processes Overview

The 17 NASA SEE processes are detailed in NPR 7123.1B. The SEHB and wall chart show how the SEE processes are integrated within each life cycle phase and repeated across multiple life cycle phases.

Table 3.1-1, SEE Mapping To Systems Engineering Handbook and NPR, is a useful resource when drilling down into the SEE process flow details, and provides a map between the SEE number, the SEHB section number, and the NPR 7123.1B section number. These numbers are also cross-linked in many of the tables in this chapter.

The practitioner should note that NPR 7123.1B provides detailed steps with process inputs and outputs for each of the 17 SEE processes.

Table 3.1-1 SEE Mapping To Systems Engineering Handbook and NPR

Life Cycle Group	SEE No.	SEHB Section No.	Process Title	NPR 7123.1B Section No.
System Design Processes	1	4.1	Stakeholder Expectations Definition	C.1.1
	2	4.2	Technical Requirements Definition	C.1.2
	3	4.3	Logical Decomposition	C.1.3
	4	4.4	Design Solution Definition	C.1.4
Product Realization Processes	5	5.1	Product Implementation	C.2.1
	6	5.2	Product Integration	C.2.2
	7	5.3	Product Verification	C.2.3
	8	5.4	Product Validation	C.2.4
	9	5.5	Product Transition	C.2.5
Technical Management Processes	10	6.1	Technical Planning	C.3.1
	11	6.2	Requirements Management	C.3.2
	12	6.3	Interface Management	C.3.3
	13	6.4	Technical Risk Management	C.3.4
	14	6.5	Configuration Management	C.3.5
	15	6.6	Technical Data Management	C.3.6
	16	6.7	Technical Assessment	C.3.7
	17	6.8	Decision Analysis	C.3.8

The approach used in this document is to utilize the NASA SEE to execute HSI activities and products. Table 3.1-2 lists the 17 SEE processes and maps them to HSI points of emphasis. This is a summary level view and will be expanded greatly in the following sections.

Table 3.1-2 Mapping HSI into the SE Engine

SYSTEM DESIGN PROCESSES	HSI EMPHASIS
Requirements Definition Processes Stakeholder Expectations Definition (1) Technical Requirements Definition (2)	Function allocation between and among systems and humans, define roles and responsibilities, develop requirements, baseline ConOps
Technical Solution Definition Logical Decomposition (3) Design Solution Definition (4)	Function allocation (during decomposition), ConOps and operations goals, iterative human-centered design, task analysis, design prototyping for HITL evaluation, operate-to documents
PRODUCT REALIZATION PROCESSES	HSI EMPHASIS
Design Realization Processes Product Implementation (5) Product Integration (6)	Validate design for all human-systems interactions as elements are integrated
Evaluation Processes Product Verification (7) Product Validation (8)	HITL Testing, validation to ConOps
Product Transition Processes Product Transition Process (9)	Prepare for Operations: training, simulations, handing and operations documents
TECHNICAL MANAGEMENT PROCESSES	HSI EMPHASIS
Technical Planning Processes (10)	LCC management
Technical Control Processes (11-15)	HSI participation in management processes, as required
Technical Assessment Process (16)	HSI products, entrance, and exit criteria for milestone reviews; TPM examples
Technical Decision Analysis Process (17)	Human-centered design, HSI domain participation

A depiction of HSI product inputs and outputs from the SEE processes using the NASA/SP-2007-6105 wall chart process flow diagram shown in Figure 3.1-1, Systems Engineering Engine with HSI Inputs and Outputs, with additional text added for HSI. This diagram will be referenced in the following sections to explain both SEE and by-phase activities to be conducted by the HSI practitioner. And as noted in section 1.2, the depictions and descriptions provided in the HSIPG attempts to aid the reader in understanding a complex, iterative, and recursive process. The reader is encouraged to use the SEHB and other sources to accompany the HSIPG .

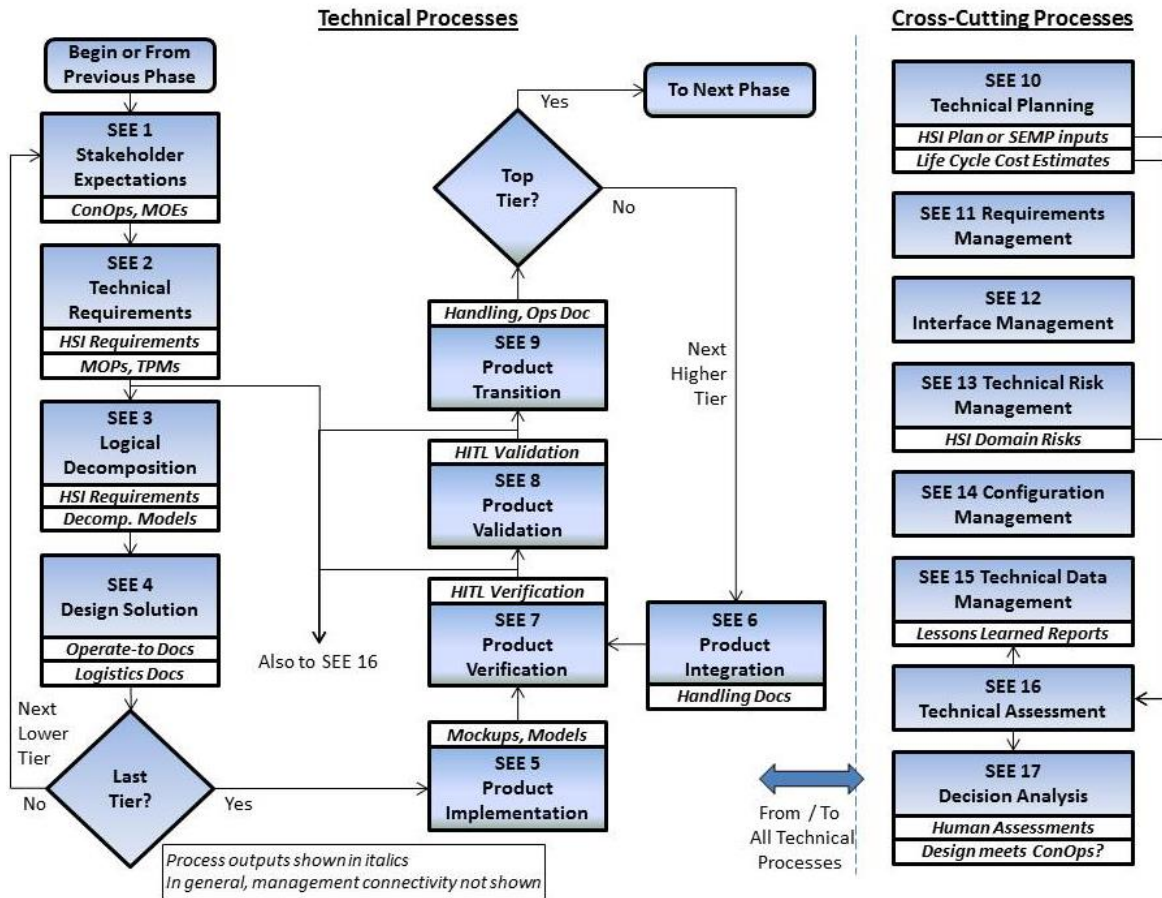


Figure 3.1-1 Systems Engineering Engine with HSI Inputs and Outputs

The HSI products shown as inputs and outputs in Figure 3.1-1 are highly condensed. The by-Phase sections of this guide use this diagram, but also refer to products in Table 3.1-3, Product Maturity Matrix for Programs and Projects. This list contains the most common products, but it should be noted that a complete list of products would be developed by the practitioner and documented in the HSI Plan. The HSI Plan should be updated as required when new products are identified. The maturity of these products is based on NPR 7120.5E.

In addition, Table 3.1-4, Product Maturity Matrix for Human-Rated Programs, is provided from NPR 8705.2B. This list will provide additional insight into the types of products required for the health, safety, and performance of humans engaging in operating and living in human-rated space vehicles.

Table 3.1-3 Product Maturity Matrix for Programs and Projects

Phase	Pre-A	A		B	C		D				E	F
Milestone Review Product	MCR	SRR	SDR/ MDR	PDR	CDR/ PRR	SIR	TRR	SAR	ORR	FRR	PLAR/ CERR	DR/ DRR
Conceptualization and Architecture												
Concept Documents, ConOps	D	I	U	U								
Function allocation to Humans (Flight Architecture)	D	I	U	U								
Function allocation to Humans (Ground Architecture)	D	D	I	U								
HSI Decomposition Models for Requirements Development	D	U	U	U								
HSI Requirements (Project and System)	D	I	U	U								
HSI Requirements (Subsystem)	D	D	D	I								
HSI inputs to technology maturation	I	U	U	U	U							
Human mockups, models, prototypes	X	X	X	X	X	X						
Human Assessments, Human-systems interactions			X	X	X	X						
Validate design to ConOps			X	X	X	X		X		X	X	
Cross-cutting and Management												
HSI Planning for SEMP or HSI Plan	D	I	U	U	U	U						
HSI-applicable Trade Study reports	X	X	X	X	X	X						
Measures of Effectiveness (MOEs)	D	D	I	U	U	U						
Measures of Performance (MOPs)	D	D	I	U	U	U						
Technical Performance Measures (TPMs)	D	D	I	U	U	U						
Life Cycle Cost Estimates	D	D	I	U	U	U	U	U	U	U	U	U
HSI Domain Risks	I	U	U	U	U	U	U	U	U	U	U	U
Lessons Learned Reports	X		X	X		X				X	X	X
Production and Operations												
Operations Concept	D	D	D	I	U	U		U	U			
Human-in-the-Loop Testing				X	X	X	X	X				
Operate-to Documents			D	D	I	U	U	U	U			
Logistics Documents			D	D	I	U	U	U	U			
Handing and Ops Documents					D	I	U	U	U	U		
Monitoring of human performance								X	X	X	X	

Legend: D – Draft, I – Initial baseline, U – Update, X - Applicable

Table 3.1-4 Product Maturity Matrix for Human-Rated Programs

Phase	Pre-A	A		B	C		D				E	F
Milestone Review Product	MCR	SRR	SDR/	PDR	CDR/	SIR	TRR	SAR	ORR	FRR	PLAR/ CERR	DR/ DRR
			MDR		PRR							
Human Rating Products and Activities												
Human-Rated Space System Description		I										
Reference Missions Description		I										
Safety and Mission Assurance Processes		I	U	U	U							
Program's Utilization of Flight Crew		I										
Human-Rating Requirements Implementation Plan		I	U	U	U							
HSI Team Plan		I										
Mandatory Technical Standards Listing		I										
Technical Standards Tailoring Summary		I										
Human-Rating Tailoring List		I	U	U	U				U			
Safety Analysis Influence Summary			I	U	U							
Crew Survival Approach Description			I	U	U							
Probabilistic Safety Requirements		I	U	U	U				U			
Crew Survival Strategy Effectiveness Summary			I	U	U				U			
Safety Risk Ranking and Probabilistic Safety Requirements Achievement Analysis			I	U	U				U			
System Failure Tolerance Summary			I	U	U				U			
Crew Workload Evaluation Plan			I	U	U							
Preliminary Flight Testing Plan			I									
Human System Performance Testing Influence Summary				I	U							
Human Error Analysis Influence Summary				I	U				U			
Flight Testing Plan and Objectives				I	U							
Verification and Validation Plan for Human Rating Requirements		I	U	U	U				U			
Human Rated System Configuration Control and Maintenance Plan									I			
Verification and Validation Results Summary for Human Rating Requirements									I			
Flight Testing Results Summary									I			
Crew Workload Evaluation Results									I			
Post-Verification/Validation Safety Analysis Influence Summary									I			

Legend: D – Draft, I – Initial baseline, U – Update, X – Applicable

3.2 By-Phase Activities and Products

The sections in this chapter are subdivided by life cycle phase since the 17 SEE processes are executed in multiple phases, which supports the iteration and recursive execution of SEE processes.

In each phase of the P/P, the HSI practitioner must be product-oriented in order to add distinct, recognizable value. Tangible products must be planned and executed on schedule and to the necessary phase-based maturity in order for HSI to be a key player in SE, in design efforts, and in mission operations. The by-phase sections will focus on both the SEE processes and product maturity goals, since products typically cut across life cycle phases.

As each product or activity is introduced for the first time, regardless of phase, additional detail and reference information will be provided.

3.3 Pre-Phase A: Concept Studies

3.3.1 Pre-Phase A Objectives

The key purpose of Pre-Phase A is to “produce a broad spectrum of ideas and alternatives for missions from which new P/Ps can be selected” (NASA/SP-2007-6105). The Pre-Phase A period is when users and stakeholders for a project or program are identified, high level requirements are compiled, preliminary design reference mission concepts are composed, possible ConOps developed, key capabilities of the systems are listed, and when request for proposal and contract-related details and deliverables for a future solicitation may be initially considered.

In order to fully appreciate the scope and nature of activities conducted during the Pre-Phase A part of the life cycle, the practitioner must understand SEE processes but also should review the detailed SEE diagram provided as an insert with NASA/SP-2007-6105 (see Table 2.2-1). It is also available online, see the References in Appendix D. An examination of the processes used in Pre-Phase A through Phase B (for Program Formulation) will show that in addition to the four system design processes (NASA/SP-2007-6105 section 4), five product realization processes from NASA/SP-2007-6105 section 5 are also performed, as well as the eight cross-cutting processes from NASA/SP-2007-6105 section 6. In the fold-out diagram, the practitioner will find that the activities listed for each SEE process are tailored to be appropriate for each phase.

Pre-Phase A NASA Systems Engineering Goals

- Produce a broad spectrum of ideas and feasible alternatives
- Determine feasibility based on cost, schedule, technical, and risk studies
- Establish mission needs, goals, and objectives

Review milestones and Key Decision Points (KDPs) for all phases are defined in section 2.3 of NPR 7120.5E. For Pre-Phase A, the Mission Concept Review (MCR), which supports KDP A for projects, is conducted near the end of Pre-Phase A.

MCR Entrance and success criteria are provided in NPR 7123.1B, Table G-3.

The MCR success criteria are fundamentally a review of the products of the activities conducted in Pre-Phase A. Ultimately it is up to the “Decision Authority” to determine if the P/P is mature and ready to progress to the next phase of the life cycle. For smaller projects, there may be a desire to go straight into Phase A and use the System Requirements Review (SRR) as the first KDP and milestone. In this case, it is strongly advised that an informal concept review be held to ensure that the concept “point of departure” is adequately communicated with stakeholders, domain experts, and team members before proceeding forward to make critical high level design decisions. It is also advised that Pre-Phase A activities and products should not be “skipped.”

It is critical that HSI practitioners actively engage in Pre-Phase A activities, reviews, and decisions to avoid costly revisions due to inadequate consideration of the human component of the P/P. The human-oriented mission goals, concepts, high level requirements, capabilities, and constraints must be clearly defined. Early inclusion of HSI practitioners ensures that the system concept is optimized for the developers, maintainers, trainers, and other system stakeholders in addition to end users. Domain personnel and SMEs can provide best practices and solutions for issues during concept development rather than later in system design when changes are more costly and more difficult to implement.

There are several HSI-related activities that must be initiated or completed during Pre-Phase A. Per **Key Concept #4**, listed in section 1.4, getting started with HSI activities early is a best practice and necessary to achieve the cost reductions (avoidance) to LCC. Incorporating HSI early sets the stage for a successful design—one that accommodates humans, rather than forces the humans to accommodate to the design. A list of important **HSI activities** is provided in this section. These activities are not strictly HSI activities; with a few exceptions, HSI does not typically “own” system-level documents such as the ConOps, SEMP, and domain-specific documents. HSI practitioners generally work inside the SE process to provide inputs for SE products.

The relevant goals for the HSI practitioner during this phase are shown in Table 3.3-1.

Table 3.3-2 Goals and Success Mapping for HSI in Pre-Phase A

Milestone	HSI Goals	HSI Success Criteria
MCR	Elicit Stakeholder Goals	Captured and quickly matured, including any provided requirements, concepts, constraints, budgets, timelines, etc.
	Support Function allocation to Humans	Must be identified early in the planning for any system, but try to avoid any “solution bias.”
	Develop Operational Concepts	Developed and evaluated against stakeholder expectations and other P/P criteria to support development of the ConOps.
	Identify Design Constraints	Document HSI factors, such as the number and skills of users, types of human interfaces, logistics infrastructure, maintainability, and training.
	Produce HSI Requirements	Captured at a high level along with stakeholder expectations
	Initiate HSI Planning	Initiated to set up resources to produce key products (standalone HSI Plan or input into the SEMP)
	Support Feasibility Activities	Conducted, which can include human-centered mockups, models, analysis, and simulations to support validation of a concept and drive considerations for alternative concepts.
	Create Metrics and Measures	Captured to provide human effectiveness and performance criteria for the proposed solutions (matured in the next phase)

Operational Concepts, as used above, can be in the form of mission scenarios, which include normal operations, as well as scenarios for emergency “off-nominal” and contingency operations. As these scenarios are developed, assumptions and conceptual decisions are made regarding how the goals and scenarios are accomplished. Functions can be allocated to hardware, software, and humans to create a system architecture concept. HSI practitioners engage to guide these decisions using best practices, analysis, and assessments for workload, human performance, reliability, and other criteria. The work is collaborative and broad, coordinating with domain experts and stakeholders.

3.3.2 Pre-Phase A Process and Products

Most activities in Pre-Phase A flow down from the primary stakeholder “Goals, Requirements, Human Allocation” activities. Performing the Pre-Phase A processes will produce HSI-related products that then support activities in repeated iterations of concept evaluation or in later phases. Figure 3.1-1 is provided as a summary view of processes to be performed. HSI is distinguished from HFE practice in that HSI is “all about process.” All of the SEE processes are important, but some processes involve the HSI practitioner more than others. The relevant processes for the HSI practitioner during this phase are shown in Table 3.3-2. Refer to the SEHB, the SEHB wall chart, and NPR 7123.1B for supporting details. NPR 7123.1B also provides detailed process flow diagrams documenting the activities as well as the inputs and outputs for each activity.

Table 3.3-3 Process-Product Mapping for HSI in Pre-Phase A

SEE Process	Process Title	Key HSI Activities	Major HSI Products Per Milestone
1	Stakeholder Expectations	Establish ConOps and support strategies for use over the systems' life, including allocation to humans	MCR: HSI inputs to mission and architecture, and ConOps (initial draft)
		Analyze expectations to establish MOEs for customer satisfaction	MCR: initial set of MOEs defined
2	Technical Requirements	Define design and product use constraints	MCR: Function allocation to humans; HSI inputs to requirements for mission, science, and top-level system
		Define functional and behavioral expectation in technical terms per ConOps/usage	
		Define technical requirements in acceptable “shall” statements	
3	Logical Decomposition	Define logical decomposition models (e.g., operator tasks) for derived requirements and validate	MCR: Initial concepts for decomposition; models used to derive HSI requirements
4	Design Solution	Define and analyze alternative design solutions for context of use and LCC	MCR: HSI inputs to technology and maturation strategies
		Verify the fully defined design solution	
5	Product Implementation	Produce early-phase reports, mockups, models, prototypes, and demonstrators	MCR: Support development of products used for human assessments
10	Technical Planning	Produce HSI content for SEMP and other technical plans	MCR: HSI Planning initiated; preliminary inputs to HSI Plan or SEMP, or equivalent

SEE Process	Process Title	Key HSI Activities	Major HSI Products Per Milestone
17	Decision Analysis	Conduct decision analysis process for identified technical issues including HSI concerns	MCR: Support architecture and mission trade-offs and analysis; coordinate decisions to allocate functions to humans

Several HSI-related products must be initiated or completed during Pre-Phase A. It should be noted that projects that have a significant human component required to achieve potentially hazardous missions may require multiple “passes” and concept design assessments. This can produce multiple assessment reports, multiple mockup configurations, and launch/landing models with thousands of simulation data runs, just to give a few examples.

These products are developed by executing the steps shown in Figure 3.1-1, Systems Engineering Engine with HSI Inputs and Outputs, which is based on NASA/SP-2007-6105 and wall chart, with HSI details added.

The process starts with **SEE 1**, Stakeholder Expectations, to elicit needs, goals, and objectives for the product and mission. The HSI practitioner will be focused on identifying the touch-points, interfaces, and systems where humans are involved or allocated to perform functions. The primary product from SEE 1 is the operations concept, which is eventually placed into the ConOps document. See chapter 4.4.2 of this document for more information on supporting ConOps development.

The second key product for the HSI practitioner will be to generate candidate measures of effectiveness (MOEs) that involve human participation. See chapter 4.4.5 of this document for developing and using HSI metrics.

Development of requirements using the stakeholder inputs and operations concepts is performed under **SEE 2**, Technical Requirements. Note: This does not include requirements management, which is SEE 11. As for all of the SEE processes, refer to NPR 7123.1B for detailed steps, inputs, and outputs. For Pre-Phase A, the requirements remain at a high level and the HSI input is focused on function allocation, which will support developing requirements in later phases. See Table 4.4-2, Function allocation Process, for details on performing function allocation activities with HSI considerations.

Typically, domain participation is ensured through collaboration when developing requirements. Although an HSI team can be formed during Pre-Phase A for larger Programs, typically the work is performed by domain and subject matter experts. Often the requirements, constraints, measures of performance (MOPs), and technical performance measures (TPMs), and related products are classified as “candidate” during this phase. See section 4.4.4 for developing HSI-based requirements, and section 4.3.2 for organizing the HSI team.

Some HSI products can be delayed to Phase A for the first draft, but most will have materials produced and planning accomplished in this phase. If the P/P is human rated, then the additional programmatic requirements are levied for compliance (e.g., HSI team stood up by SRR per NPR 8705.2B). Capturing the planning materials produced during Pre-Phase A is important to be able to feed into the HSI Plan, if written, or the SEMP or similar engineering management document. This activity is performed under **SEE 10**, Technical Planning, which is a cross-cutting process. See HSIPG section 4.4.1 on writing the HSI Plan.

The products from SEE 1 and SEE 2, along with other decisional information, will feed **SEE 3**, Logical Decomposition, activities. During Pre-Phase A, the HSI practitioner should start to identify which mechanisms and models will be used to strategically derive and decompose detailed requirements. These methods can include a variety of human assessments from low-fidelity mockups, task analysis, human constraints and standards, human-centric design guidance, etc. For a list of these types of resources, refer to the References in Appendix D. See section 4.4.7 for ensuring the usability of systems and section 4.3.4 on identifying human-centered trade-offs.

The Design Solution process, **SEE 4**, follows next and uses the Pre-Phase A products to develop the set of potential solutions, recommended architectures, and inputs to the technology and maturation strategies. The HSI practitioner participates to ensure the design solution options are validated against the human goals and objectives, and concept documents. Plus the HSI practitioner can ensure that any LCC analysis includes the full scope of the life cycle, which includes an evaluation of the cost of operational resources and activities for each design alternative. This work is supported by **SEE 17**, Decision Analysis, which uses the Pre-Phase-A products as inputs, and provides overall decisional outcomes for the P/P. See HSIPG sections 4.4.9 and 4.4.10 for LCC as it applies to HSI.

While not explicitly listed in Table 3.3-2, the HSI practitioner should also participate in **SEE 13**, Technical Risk Management, which also includes risk analysis activities.

Prototyping and modeling can be extensive for projects, which combine human habitability, operations, and conducting science such as a crew vehicle or similar manned platform. These physical products are produced in **SEE 5**, Product Implementation. Figure 3.3-1 is a photograph of a crew vehicle mockup that was used in an HITL to analyze access, reach, and visual perception. As you can see, a modest investment was made to construct a structurally stable model that could be reconfigured inside. Figure 3.3-2 shows a mockup for an aviation cockpit for evaluation of pilot performance. The pilot is outfitted with an eye-tracking device to gain insight into both the layout and human performance when managing concurrent tasks. While some HITL mockups can and should be elaborate, in many cases prototypes need not be overly detailed or costly to provide valuable design information. The systems engineer should be well

aware that the end product includes not only the final deliverable, but enabling products as well. A rocket cannot be sent to space without the availability of an integration and assembly facility. Also, reducing risk is a key component of human space flight; mockups and models are stepping stones along the way to both successful, well-crafted solutions and for ensuring the safety of the operators.



Figure 3.3-1 Example: Crew Vehicle Mockup



Figure 3.3-2 Example: Cognitive Performance in Aviation Environment

Although not explicitly listed in Table 3.3-2, additional product realization processes are executed as shown in Figure 3.1-1 to verify, validate, and integrate (**SEE 6**) any products created in SEE 5, Product Implementation. The HSI practitioner may be involved in these processes. For Pre-Phase A, **SEE 7**, Product Verification and **SEE 8**, Product Verification, are usually limited to products produced in the phase, for example mockups and models.

3.4 Phase A: Concept & Technology Development

3.4.1 Phase A Objectives

The key purpose of Phase A is to “determine the feasibility and desirability of a suggested new major system and establish an initial baseline compatibility with NASA’s strategic plans” (per NASA/SP-2007-6105). This is a stage in which the mission concept from Pre-Phase A is revisited in a more formal fashion, with increased emphasis towards conceptual development, engineering details, technical risks, and allocation of functions to various systems and sub-systems. The goals for Phase A from the NASA/SP-2007-6105 wall poster are shown in the “blue box” that follows to provide a reference for the phase from a high level perspective.

Phase A NASA Systems Engineering Goals
<ul style="list-style-type: none"> • Develop baseline mission concept • Demonstrate feasibility of selected concept • Establish validated requirements that meet mission objectives • Establish architectural product design • Allocate requirements to next lower level • Identify needed technologies • Mitigate technical risks

In Phase A, the work that was completed in Pre-Phase A is used to begin the more formal work and rigor required of space flight P/Ps. This is still early in the P/P life cycle, so decisions made here are critical and greatly affect LCC. The architects, designers, and SMEs are still given “room” to assess alternative design solutions during the beginning of the phase. By the end of the phase, the concepts, documents, requirements, and solutions become firm as system trades, assessments, technology selection and solutions iterate back and forth in the effort to seek the most cost-effective designs. The result of the phase is an **accepted baseline design**, which is achieved through the two life-cycle reviews, the SRR and the System Design Review (SDR). Robotic missions use the Mission Design Review (MDR) in place of the SDR. HSI is still applicable to robotic missions.

The SRR is generally a mid-phase review. The SRR precedes the MDR or SDR.

The MDR or SDR support the KDP B milestone. For programs, the SRR and SDR support the KDP 0 milestone. Entrance and success criteria are provided in NPR 7123.1B, Appendix G, as follows:

- Table G-1 - SRR for a Program
- Table G-4 - SRR for Projects or Single-project Programs
- Table G-2 - SDR for a Program
- Table G-5 - MDR/SDR for Projects and Single-project Programs

In the event that the MCR was not held during Pre-Phase A, HSI practitioners are strongly advised to communicate the concepts and human performance goals to stakeholders, domain experts, and team members, well in advance of SRR to ensure that the human component is taken into consideration for the Phase A work flow. For SRR and MDR/SDR, HSI practitioners support the reviews with HSI-related product submissions, as defined in the HSI Plan, as peers to communicate HSI details when required, and as evaluators to ensure compliance to best practices and standards.

Phase A goals and success criteria are mapped to relevant milestones in Table 3.4-1.

Table 3.4-1 Goals and Success Mapping for HSI in Phase A

Milestone	HSI Goals	HSI Success Criteria
SRR	Support Function allocation to Humans	Completed for all established architecture levels
	Establish HSI Team (required for Human-rated Programs and recommended for most Projects)	HSI Team Roster includes Lead and all necessary SMEs
	Generate HSI Requirements	HSI design constraints, human interfaces, and objectives for all relevant domains are addressed in requirements
	Support Concept of Operations	HSI Inputs Incorporated into ConOps
SDR/ MDR	Initiate HSI Planning	Key HSI products and HSI resources are documented in HSI Plan, or as input to SEMP or other project plan document
	Support Feasibility Assessments and Modeling	Human-centered mockups, models, simulations and analyses are utilized to drive lower level requirements and design trades

3.4.2 Phase A Process and Products

The activities performed in Phase A are similar to those performed in Pre-Phase A. Indeed, smaller projects can easily lose the distinction between these two early phases as the milestone and decision gate for Pre-Phase A, the MCR, is often ignored in favor of the first Phase A KDP milestone, the SRR. A review of the tailoring of the activities performed in Phase A as shown in the wall-chart provided with NASA/SP-2007-6105 shows moving from candidate architecture, requirements, and solutions in Pre-Phase A to selected and baselined architecture, requirements, and solutions in Phase A.

A second distinction between Pre-Phase A and Phase A lies with the depth of decomposition: Phase A activities will iterate to a lower and more detailed level, having completed selection of higher level parts of the design.

As the P/P is matured, the ability to perform additional processes is made available. For example, firming the architecture allows for the development of TPMs, improved LCC estimates, higher fidelity models and mockups, and the creation of product baselines.

HSI practitioners will be called upon to engage in activities as shown in Table 3.4-2, Process-Product Mapping for HSI in Phase A. Some activities and products are similar to those in Pre-Phase A.

Table 3.4-2 Process-Product Mapping for HSI in Phase A

SEE Process	SEE Process Title	Key HSI Activities	Major HSI Products Per Milestone
1	Stakeholder Expectations	Establish ConOps and support strategies for use over the systems' life, including allocation to humans	SRR: Baseline ConOps S/MDR: HSI input to ConOps updated from previous version
		Analyze expectations to establish MOEs for customer satisfaction	SRR: HSI MOEs captured to drive HSI MOPs, TPMs
2	Technical Requirements	<ul style="list-style-type: none"> Define design and product use constraints Define functional and behavioral expectation in technical terms per ConOps/usage Define technical requirements in acceptable "shall" statements 	SRR: HSI Requirements baselined for established architecture S/MDR: HSI Requirements updated for new human allocation or changes
		Use MOEs to create MOPs and TPMs for HSI success	S/MDR: HSI MOPs, TPMs established for tracking
3	Logical Decomposition	Define logical decomposition models (e.g., operator tasks) for derived requirements and validate	SRR: Decomposition Models, Derived Requirements to develop lower level design. S/MDR: iterate as needed for each level of architecture

SEE Process	SEE Process Title	Key HSI Activities	Major HSI Products Per Milestone
4	Design Solution	Define and analyze alternative design solutions for context of use and LCC	SRR: Identify functions allocated to humans and update HSI plans
		Verify/validate the fully defined design solution against the ConOps	S/MDR: Iterate for new design levels
		Prepare Logistics and Operate-to Procedures	S/MDR: Procedures (draft)
5	Product Implementation	Produce early-phase reports, mockups, models, prototypes, and demonstrators	SRR, S/MDR: Support development of product used for human assessments
6	Product Integration	Support production of human-centered phase end-items from SEE 5	SRR, S/MDR: Assess human element for integration
7	Product Verification	Verification of SEE 5 products	SRR, S/MDR: Verified phase product end-items created in SEE 5
8	Product Validation	Validation of SEE 5 products, Evaluate design solutions against ConOps	SRR, S/MDR: Validated phase product end-items created in SEE 5
10	Technical Planning	Provide HSI inputs to SEMP (or equivalent) and other technical plans	SRR: HSI Planning started S/MDR: HSI Plan or equivalent (draft)
		Provide HSI inputs to LCC estimates	SRR, S/MDR: LCC estimates as needed
13	Technical Risk Management	Assess and create mitigation plans for HSI Domain risks	SRR, S/MDR: HSI Domain Risks as needed
17	Decision Analysis	Conduct decision analysis process for identified technical issues including HSI concerns	SRR, S/MDR: Human-centric assessments for established architecture

The key HSI products started in Pre-Phase A are brought to baseline configuration during Phase A, as shown in Table 3.1-3, Product Maturity Matrix for Programs and Projects. These products are matured by performing the steps as shown in Figure 3.1-1, SEE with HSI Inputs and Outputs.

Note: The following description of NASA SEE processes is not unique to HSI.

Stakeholder expectations, **SEE 1**, are revisited, validated, and formalized and used to mature the ConOps document and create MOEs, which must be established for SRR.

These SEE 1 and Pre-Phase A products are then used in the steps for **SEE 2**, Technical Requirements, to create top level requirements. The MOEs are used to create MOPs and TPMs as the requirements are matured. Refer to section 4.4.5 for additional information on HSI measures.

Most of the requirements work is completed for the top level architecture by SRR. Additional levels of the architecture are then derived from the top level, sometimes with unique milestones.

Decomposition models are selected and used in **SEE 3** to further derive requirements. Decomposition models can include human-centric models such as timing diagrams, crew timelines, behavior diagrams, and operator task analysis. Critical decisions regarding function allocation are made. This may include determinations regarding autonomy and automation as well.

For complex systems, human assessments are performed in **SEE 17**, Decision Analysis, often per technical planning under **SEE 10**. Process **SEE 13**, Technical Risk Management, also includes probabilistic risk assessment. These cross-cutting processes inform the nine technical processes (SEE 10 – 17) and can drive and affect the activities in those processes, especially for HSI, in early life cycle phases.

The HSI requirements and decomposition models are used in **SEE 4** to produce the candidate design solutions and alternatives. HSI practitioners should engage to analyze the design solutions for P/P systems that require extensive human involvement.

The practitioners should also engage to validate the design solution against the ConOps, as part of **SEE 8**. Any systems that are allocated to humans are identified and the HSI Plan or equivalent documentation is updated to reflect the need to address HSI domain considerations for those systems.

HSI practitioners will participate to ensure that early-phase proof of concept and prototype products are developed. These products are the output of **SEE 5**, Product Implementation, and take inputs primarily from the SEE 4 and SEE 17. These models and mock-ups can aid in the development of requirements and design constraints, and will also provide feedback to **SEE 16**, Technical Assessment process.

As shown in the Table 3.3-2, HSI practitioners will likely be engaged in the remaining processes in the product realization group: Product Verification (**SEE 7**), Product Validation (**SEE 8**), and Product Integration (**SEE 6**). These processes are shown in Figure 3.1-1, Systems Engineering Engine with HSI Inputs and Outputs. A list of potential human-centered design evaluations and products, useful for SEE 7 and SEE 8, can be found in NASA/TP-2014-218556.

The SRR is the first milestone gate for a review of the requirements, technical plans, and initial ConOps document. The TPMs are baselined for SDR, where the candidate design is established as the baseline. The simplicity of the products in Table 3.4-2 somewhat masks the significant amount of effort and rigor required to complete the activities to produce the products. Complex systems can require significant effort to assess options, build mockups, write software models, plan future HSI activities, and create documents.

It is not practical to detail all of the specific HSI products required for a specific P/P—and, indeed, that is the role of the HSI Plan. The number and types of evaluations, mockups, human interaction assessments, task and user evaluation, HITL tests, etc. will depend entirely upon the nature and scope of the P/P and the fidelity of the evaluation. This is another reason why working to develop the HSI plan from the beginning of the P/P is essential.

3.5 Phase B: Preliminary Design and Technology Completion

3.5.1 Phase B Objectives

The key purpose of Phase B is to “define the project in enough detail to establish an initial baseline capable of meeting mission needs” (NASA/SP-2007-6105). Within Phase B, if not already, requirements will be flowed down from a Level 1 agency collection, to Level 2, 3, and possibly other levels as needed by the system and required by any relevant contracts.

Phase B NASA Systems Engineering Goals

- Establish a design solution that meets mission needs
- Establish design dependent requirements and interfaces
- Complete “implementation” level of design

In Phase B, the work that was completed in Phase A is developed and matured to support baselining of the design solution. The processes mature, leading to updates to plans, risk assessments, and process documentation prior to the PDR. Phase A system trades, assessments, technology selection and solutions are iterated, leading to the concepts, documents, requirements, and solutions reaching maturity levels necessary to be reviewed, refined, and baselined by the end of the phase. The conclusion of the phase is a **selected design solution**, which is achieved through the PDR.

Completion of the PDR precedes the KDP C milestone for projects. For programs, PDR supports KDP I. Entrance and success criteria of the PDR are provided in NPR 7123.1B, Appendix G, Table G-6.

HSI practitioners support PDR with HSI-related product submissions and through review of design features from an HSI perspective.

Goals and Success Mapping for HSI in Phase B are provided in Table 3.5-1.

Table 3.5-1 Goals and Success Mapping for HSI in Phase B

Milestone	HSI Goal	HSI Success Criteria
PDR	Refine requirements; form and validate derived Human requirements	The top-level human requirements, including mission success criteria, TPMS, and any sponsor-imposed constraints are agreed upon, finalized, stated clearly, and consistent with the preliminary design. The flow down of verifiable requirements is complete and proper.
	Update SEMP, HSI Plan, and other technical plans	Definition of the technical interfaces (both external entities and between internal elements) is consistent with the overall technical maturity and provides an acceptable level of risk.
	Refine, validate, and document technical requirements	The operational concept is technically sound, includes human systems, and includes the flow down of requirements for its execution. Technical trade studies are mostly complete in sufficient detail and the remaining trade studies are identified, plans exist for their closure, and potential impacts are understood.
	Refine interfaces and evaluate compatibility	Appropriate modeling and analytical results are available and have been considered in the design.

3.5.2 Phase B Process and Products

Since many Phase B activities are continuations or maturations of activities initially begun in Phase A, Phase B shares many of the key items for HSI team members to continue supporting. However, there is often a greater opportunity for engagement in HITL testing using mockups and software simulators, as well as trade studies evaluating various design options. Thus, human factors activities have a key role in Phase B, beyond that of requirements definition, getting into true design evaluation and maturation.

A review of the tailoring of the activities performed in Phase B as shown in the wall-chart provided with NASA/SP-2007-6105 shows moving from selected and baselined architecture, requirements, and solutions in Phase A to a selected design solution in Phase B.

Processes developed in Phase A continue to be refined, allowing for system design to be solidified. Product baselines are iterated and updated, human-system interactions evaluated, and trades performed. Table 3.5-2 provides a map to the additional key HSI processes being performed in Phase B. Note that the processes executed in the previous phases are still being performed iteratively.

Table 3.5-2 Process-Product Mapping for HSI in Phase B

SEE Process	Process Title	Key HSI Activities	Major HSI Products per Milestone
2	Technical Requirements	Define TPMs for human performance	PDR: HSI MOPs refined, TPMs defined and tracked
3	Logical Decomposition	Refine requirements; form and validate derived Human requirements	PDR: Requirements iterated and refined for preliminary design; ConOps further developed and matured
4	Design Solution	Prepare for detailed design, manufacturing, and testing	PDR: Support initial development of manufacturing, logistics, training, and testing plans
5	Product Implementation	Produce mockups, models, prototypes, and demonstrators	PDR: Support development of products used for human assessments
6	Product Integration	Ensure solution is compatible with integration philosophy	PDR: Plans/processes for integration of lower tier products
7	Product Verification	Prepare to conduct verification; conduct trial verification for high risk items	PDR: Models and prototypes are planned and developed; Crew Task Analyses conducted
8	Product Validation	Prepare to conduct validation; conduct trial verification for high risk items; evaluate design against ConOps	PDR: Models and prototypes are planned and developed
10	Technical Planning	HSI inputs to SEMP, HSI Plan, and other technical plans	PDR: HSI Plan iteration and update
13	Technical Risk Management	Conduct technical risk assessment; implement mitigation plans	PDR: HSI Plan, HSI Domain plans, and P/P risk management plans
17	Decision Analysis	Conduct decision analysis process for identified technical issues including HSI concerns	PDR: HSI process feedback iterations at each milestone

The key HSI products started in Phase A are updated during Phase B, as shown in Table 3.1-3, Product Maturity Matrix for Programs and Projects. The PDR is the milestone gate for review of the requirements, technical plans, interface control documents, and V&V documents.

HSI practitioner inputs support meeting PDR Entrance Criteria via the HSI Plan, Human Rating Certification Package, Verification/Validation Plan, trade-off analyses, and various other products.

SEE 2, Technical Requirements, are refined, along with development of human-related metrics to allow for tracking of metrics through the remaining phases.

The requirement allocation in **SEE 3** produces more detailed requirements and operational concepts influenced by the results of Phase A **SEE 4** and **SEE 5** modeling, prototyping, and validation activities. Those activities continue in Phase B, along with preliminary preparation for Phase C manufacturing, logistics, training, and testing activities and products. A Preliminary hazard analysis ensures that safety requirements have been adequately addressed in system design.

HSI practitioners provide support for many **SEE 7** and **SEE 8** V&V activities during Phase B, providing feedback to system designers, requirements developers, and producers of the various PDR products. HITL activities conducted in Phase B can often be “pre-declared” for V&V credit, which is typically conducted in Phase D.

SEE 6, project integration activities, ensures that tiered functionalities are documented and communicated between stakeholders at all development levels. Expectations for integration are established in support of PDR. **SEE 10**, **SEE 13**, and **SEE 17** activities also directly support the PDR milestone review, as plans, processes, and other products are developed and matured.

The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design. This is a critical milestone for HSI practitioners, as it is the first full review of system design from concept through verification, validation, and operations. The positive evidence of HSI influences should be visible through early risk reductions, extensive human-system integration, and a mature human-centered design concept.

3.6 Phase C: Final Design & Fabrication

3.6.1 Phase C Objectives

The key purpose of Phase C is to “complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software” (NASA/SP-2007-6105). In essence, this phase occurs when all design details are finalized and the system is prepared for testing and verification.

Phase C NASA Systems Engineering Goals

- Establish complete, validated detailed design
- Complete all design specialty audits
- Establish manufacturability processes and controls
- Finalize and integrate interfaces
- Produce items that conform to specs and acceptance criteria
- Prepare facilities for production

In Phase C, the work design solution that was selected in Phase B is prepared for finalization and fabrication. The processes mature similarly, further mitigating risks, developing technological readiness, optimizing design trades, and proceeding through the milestones. Phase B system trades, assessments, technology selection and solutions complete design iterations, leading to the start of production of the final design solution by the end of the phase. The conclusion of the phase is an **end product**, which is achieved by working the processes and proceeding through the Critical Design Review (CDR), Production Readiness Review (PRR), and System Integration Review (SIR). To ensure readiness for production, a PRR and SIR may be held. For many projects, the intent of these reviews will be met during the project's CDR.

For projects, the CDR, PRR, and SIR support KDP D. For programs, the CDR and SIR support KDP II. (See NPR 7120.5E, section 2.3 for complete details.)

The Phase C milestone entrance and success criteria are provided in NPR 7123.1B as follows:

- Table G-7 - CDR for Program
- Table G-8 - PRR for Project
- Table G-9 - SIR for Program

Table 3.6-1 provide Goals and Success Mapping for HSI in Phase C.

Table 3.6-1 Goals and Success Mapping for HSI in Phase C

Milestone	HSI Goal	HSI Success Criteria
CDR	Verify detailed design meets system requirements	Detailed human requirements, verification requirements, and integration requirements are developed and baselined. The flow down of verifiable requirements is complete and proper.
	Update SEMP, HSI Plan, and other technical plans	Definition of the technical interfaces (both external entities and between internal elements) is consistent with the overall technical maturity and provides an acceptable level of risk.
	Refine and document technical plans	Technical trade studies are complete to sufficient detail and incorporated into detailed design.
	Evaluate interface compatibility	Model/prototype components and interfaces. Incorporate initial results into detailed design. Validate components and interfaces against the operational concept.

3.6.2 Phase C Process and Products

Phase C shares many of the key items for HSI team members to continue supporting. In this phase, the detailed design is matured based on the results of Phase B HITL testing, simulations, and trade studies. Design evaluation and maturation lead to Phase D assembly, integration, and test activities.

A review of the tailoring of the activities performed in Phase C as shown in the wall-chart provided with NASA/SP-2007-6105 shows the P/P moving from selected design solution architecture, requirements, and solutions in Phase B to an end product in Phase C.

Processes developed in prior phases continue to be implemented. Product baselines are utilized to prepare for production; human-system interactions are evaluated for operations and training products; and technological readiness is reevaluated. Table 3.6-2 provides a map to the additional key HSI processes being performed in Phase C.

Table 3.6-2 Process-Product Mapping for HSI in Phase C

SEE Process	Process Title	Key HSI Activities	Major HSI Products per Milestone
4	Design Solution	Mature detailed design, manufacturing, and testing plans	CDR/PRR/SIR: Detailed manufacturing, logistics, training, and testing plans baselined/updated
5	Product Implementation	Generate and update detailed implementation plans and procedures	CDR/PRR: Finalize design updates based on human assessments SIR: Integrated HSI inputs evolved from individual component inputs
6	Product Integration	Review/generate detailed integration plans and procedures	CDR/PRR/SIR: Integrated lower tiered products
7	Product Verification	Conduct verification activities	CDR/PRR/SIR: Verification results to show that system models/prototypes satisfy requirements prior to production
8	Product Validation	Evaluate design against ConOps	CDR/PRR/SIR: Validation results to show that system models/prototypes satisfy operational intent
10	Technical Planning	HSI inputs to SEMP, HSI Plan, and other technical plans	CDR/PRR: HSI Plan iteration and update with focus on training and operational phases. SIR: Integrated HSI inputs evolved from individual component inputs
13	Technical Risk Management	Conduct technical risk assessment; implement mitigation plans	CDR/PRR: HSI Plan, HSI Domain plans, and P/P risk management plans updated for production and operational risks SIR: Integrated HSI inputs evolved from individual component inputs

SEE Process	Process Title	Key HSI Activities	Major HSI Products per Milestone
16	Technical Assessment	Assess product against plans and requirements	CDR/PRR: Assess detailed design to determine suitability prior to production SIR: Integrated HSI inputs evolved from individual component inputs
17	Decision Analysis	Conduct decision analysis process for identified technical issues including HSI concerns	CDR/PRR/SIR: HSI process feedback iterations at each milestone

The key HSI products finalized to prepare for system production during Phase C, as shown in Table 3.1-3, HSI Product Maturity. The CDR is the major milestone gate for review of the requirements, technical plans, interface control documents, and V&V documents.

Phase B preliminary V&V activities are continued and matured in Phase C **SEE 7** and **SEE 8** activities, establishing a greater level of confidence that the detailed design will meet the requirements and operational intent of the system. Models and prototypes are refined as **SEE 4** requirements and **SEE 5** plans are generated in support of system CDR.

Production and operational risks are identified and mitigated through trades and documented in support of **SEE 13**, **SEE 16**, and **SEE 17** milestone review preparation. To prepare for Phase D system assembly and integration, **SEE 10** Technical Planning activities focus on the production and operation of the system, making use of knowledge gained from a continued HSI focus on design for producibility, safety, maintainability, training, and operation. A hazard analysis ensures that safety requirements have been adequately addressed in system design. **SEE 6** project integration activities integrate products from all development tiers in order to support development of integrated end-item documentation for CDR.

The CDR demonstrates that the maturity of the design is appropriate to support proceeding with full-scale fabrication, assembly, integration, and test. CDR determines that the technical effort is on track to complete the system development, meeting performance requirements within the identified cost and schedule constraints. For HSI practitioners, this milestone represents the conclusion of the system design and a shift of focus to further improving system operation through efficiencies in training, operation planning, and maintenance. The early involvement of training, operations, and maintenance personnel in the development of ConOps, requirements, and models/prototypes should be very evident as human-system features enable HSI practitioners to continue to reduce LCCs by optimizing system interactions rather than trying to fix costly design flaws during this phase.

The positive evidence of HSI influences should be visible through available optimization opportunities and reduction of design flaws compared to legacy programs.

3.7 Phase D: System Assembly, Integration & Test, Launch

3.7.1 Phase D Objectives

The purpose of Phase D is to “assemble, integrate, verify, validate, and launch the system, meanwhile developing the confidence that it will be able to meet the systems requirements” (NASA/SP-2007-6105). This includes conducting the Test Readiness Review (TRR), the System Acceptance Review (SAR), Operational Readiness Review (ORR), and the Flight Readiness Review (FRR). These reviews ensure the system is built to required specifications, risks have been appropriately mitigated, and that the system is ready for a safe and successful mission. Other Phase D activities include updating operational procedures, rehearsals and training of operating personnel and crewmembers, and implementation of the logistics and spares planning.

Phase D NASA Systems Engineering Goals

- Assemble and integrate system
- Verify and validate system
- Accept system
- Integrate pre-launch system
- Establish readiness to launch/deploy system

In Phase D, the HSI team is focused on the V&V processes that typically begin after CDR, as the end product is integrated for testing. The HSI team has goals to develop the necessary verification closure evidence for all HSI requirements and to further reduce mission risk through validation of the end product for its intended use as described in the ConOps. HSI goals are also to ensure that mission operational products are completed and operators are trained and certified for their work during the operations phase. End product system-level and/or flight testing typically occur during Phase D, and the HSI team's goal is to implement the human system aspects of flight test planning, execution, data analysis, and reporting. Phase D HSI goals and success criteria are mapped to relevant milestones in Table 3.7-1.

The Phase D milestone entrance and success criteria are provided in NPR 7123.1B as follows:

- Table G-10 - TRR Entrance and Success Criteria
- Table G-11 - SAR Entrance and Success Criteria
- Table G-12 - ORR Entrance and Success Criteria
- Table G-13 - FRR Entrance and Success Criteria.

Table 3.7-1 Goals and Success Mapping for HSI in Phase D

Milestone	HSI Goals	HSI Success Criteria
TRR	Complete HSI preparation for and endorsement of end product system-level/flight test	Comprehensive HSI input to appropriate system-level test objectives, requirements, plans and procedures
SAR	Complete Verification of HSI Requirements	End product system is shown to conform to the HSI requirements
	Complete End Product Validation	End product meets the users' needs in the operational mission context
	Complete Development of HSI Input to Operations Support Products	Operations support products accepted by end users
ORR/FRR	Certify the System for Operations with Humans	HSI team's endorsement of system certification, leading to operations and sustainment
	Train and Certify the Users for Operations with the System	HSI team's endorsement of user certification, leading to operations and sustainment

3.7.2 Phase D Process and Products

The V&V activities completed in Phase D are particularly relevant to the HSI Team. The HSI requirements are verified based upon the verification statements and rationales written and refined from as early as Pre-Phase A. Proper interpretation of these requirements is critical, and continuing insight and oversight are needed for the HSI Team to ensure success in this phase.

Validation of the end product system's operational effectiveness is also key in this phase. Validation events are conducted and reported, and the HSI team is involved in these activities, generation and review of the resulting product reports.

Human-in-the-loop (HITL) activities conducted in earlier phases that were "pre-declared" for verification credit are now assessed for closing requirements. The HSI Team ensures that these HITL activities are consistent with the "test the way we fly" or "test as you fly" principle described in NASA/SP-2007-6105, in order to use them for verification closures.

The HSI team engages in the system-level test/flight test planning, execution, data analysis, and reporting. The team provides HSI input to appropriate system-level test objectives, requirements, plans and procedures, and test reports. Test data necessary to validate HSI analytical models is collected and used in model correlation.

The HSI Team supports users of the system in completion of their pre-deployment training.

HSI practitioners will be called upon to engage in activities as shown in Table 3.7-2, Process-Product Mapping for HSI in Phase D.

Table 3.7-2 Process-Product Mapping for HSI in Phase D

SEE Process	SEE Process Title	Key HSI Activities	Major HSI Products Per Milestone
6	Product Integration	Support system integration as appropriate	TRR: HSI input to system-level test plans
7	Product Verification	Conduct verification of the human system requirements	SAR: Requirement verification closure reports from HITL test/demonstration and from HSI inspections and analyses
8	Product Validation	Complete validation events that demonstrate the end product meets user needs in accordance with the ConOps	TRR: HSI input to system-level test plans/flight test plans SAR: Product validation reports from HITL test/demonstration and from HSI inspections and analyses SAR: System-level test and/or flight test reports that provide validation of the end product and provide data for validation of analytical models used to predict system performance
9	Product Transition	Provide HSI input to the technical reviews that support transition of the end product to its intended user for operations	SAR: HSI inputs to operations and maintenance manuals, procedures, and training packages SAR: HSI inputs to system design data books and other supporting technical materials for use during Phase E SAR: Validated HSI analytical models of the end product system
		Generate HSI objective evidence of the acceptability of the end product and its operational mission	ORR/FRR: HSI inputs to the system certification package (e.g. Human Rating Certification Package)
13	Technical Risk Management	Conduct technical risk assessment; implement mitigation plans	ORR/FRR: HSI inputs to P/P risk management plans updated with all prelaunch mitigations

HSI system development products are finalized during Phase D, as shown in Table 3.1-3, Product Maturity Matrix for Programs and Projects. These products are matured by performing the steps as shown in Figure 3.1-1, Systems Engineering Engine with HSI Inputs and Outputs, for **SEE 6**, **SEE 7**, **SEE 8**, **SEE 9** and **SEE 13**.

The TRR ensures P/P readiness for a major system-level test, such as a space system flight test. HSI input to the preparation and planning for this test is part of the TRR package.

The SAR provides for acceptance of the end product system by the operational P/P user. HSI input to the SAR package includes complete V&V reporting on HSI aspects of requirements and operational concepts. It also includes validated analytical models provided by HSI domain experts, and HSI input to operational support products such as training documentation, and manuals and procedures for operation and maintenance of the end product system.

The ORR/FRR are the milestones for defining P/P readiness to move into Phase E operations. HSI products include objective evidence of the acceptability of all human system aspects of the end product in its operational mission context. This evidence informs the system certification package (e.g., Human Rating Certification Package), which will be the focus of the Agency and its TAs as they endorse the end product readiness for transition to user operations.

3.8 Phase E: Operations and Sustainment

3.8.1 Phase E Objectives

The Operations & Sustainment Phase, Phase E, is focused upon conducting the mission, meeting the initially identified need, and maintaining support for that need. The HSI team role in Phase E focuses on identifying which aspects of the as-built system are operationally successful and which are not. HSI lessons learned are generated from a variety of sources including:

- Inflight testing and demonstration of HSI aspects of the mission/system
- User/crew debriefs and interviews
- Collection of human system data (e.g., errors, losses of efficiency, incidents, accidents)
- Collection of human performance data (e.g., crew time / task time)
- Collection of physiologic indicators (e.g., consumables usage, vital signs, illness/injury rates)
- Mission data and reports.

These sources of information should be carefully reviewed and synthesized, lessons learned captured, and HSI findings documented in reports or publications for the ongoing operations and to benefit future P/P.

The health and safety of all ground and flight personnel are critical criteria for evaluating the success of the operations and sustainment phase of the P/P. The HSI team is key to maintaining personnel health and safety, leading directly to successful human performance in mission operations, which enables the success of the overall P/P through its operational phase.

Phase E NASA Systems Engineering Goals

- Perform mission
- Sustain system
- Improve/augment system

In Phase E, the HSI team is focused on observing the HSI aspects of the operating system and its users/maintainers to ensure human safety, health, and performance in operations. The HSI team aims to document and communicate specific aspects of operations that need improvement to achieve P/P mission success and human safety, health, and performance objectives. A complementary goal is to document those aspects of the mission-system that are fully successful due to HSI effort during development.

Phase E HSI goals and success criteria are mapped to the relevant milestones in Table 3.8-1. The Post-Launch Assessment Review (PLAR) evaluates the readiness of the spacecraft systems to proceed with full, routine operations after post-launch deployment. The review also evaluates the status of the project plans and the capability to conduct the mission with emphasis on near-term operations and mission-critical events. The HSI team supports the PLAR with an evaluation of human-system aspects of the operational system's readiness to proceed into full operations.

Table 3.8-1 Goals and Success Mapping for HSI in Phase E

Milestone	HSI Goals	HSI Success Criteria
PLAR, CERR, PFAR	Ensure user/maintainer safety, health, and performance	Safe and productive operations of the system to accomplish the defined mission
PLAR, CERR, PFAR	Identify mission-system anomalies and operational aspects that need improvement in relation to users and maintainers	Documented lessons learned are provided to the P/P for implementation of necessary corrections and improvements
PLAR, CERR, PFAR	Identify mission-system operational aspects that are fully successful in relation to users and maintainers, with linkage to HSI effort during the P/P development phases	Documented lessons learned are provided to the P/P to demonstrate an operational return on HSI investment made during system development
DR	Capture HSI knowledge gained over the course of the P/P	HSI knowledge is placed into the P/P documentation system

The Critical Events Readiness Review (CERR) evaluates the readiness of the project and the flight system to execute a critical event during flight operation. The HSI team provides inputs to CERR, for example, the human-system readiness to perform an extravehicular activity (EVA).

The Post-Flight Assessment Review (PFAR) evaluates how well mission objectives were met during a mission, identifies all flight and ground system anomalies that occurred during the flight, and determines the actions necessary to mitigate or resolve the anomalies for future flights of the same spacecraft design. The HSI team describes the success of human-system mission objectives, lessons learned from the flight, and improvements needed for further operations of the system.

The Decommissioning Review (DR) confirms the decision to terminate or decommission the system and assesses the readiness of the system for the safe decommissioning and disposal of system assets. The HSI team may have additional lessons learned from the final stages of the mission, and final values for TPMs evaluated during the operational phase.

The Phase E milestone entrance and success criteria are provided in NPR 7123.1B as follows:

- Table G-14 - PLAR Entrance and Success Criteria
- Table G-15 - CERR Entrance and Success Criteria
- Table G-16 - PFAR Entrance and Success Criteria.

3.8.2 Phase E Process and Products

Specific HSI team activities in this phase include sustaining engineering of the mission system while it is being operated, operational monitoring, data collection on the safety, health, and performance of the humans involved with the mission system, and documentation of new HSI knowledge generated during this phase. The HSI team produces technical analyses on potential operational improvements and on successful operational outcomes due to HSI effort performed during system development. For operational flight testing, the HSI team produces reports on Flight Test Objective outcomes that may validate the integrated end product or contribute to the validation of analytical models of the system. As part of HSI sustaining effort, the team evaluates upgraded operational methods and system features as alternate solutions for issues emerging during the mission. Appendix C.2 provides an example of sustaining lessons learned for Shuttle. Examples of crew time as a key measure is cited throughout this document, as well.

Table 3.8-2 defines HSI products resulting from these activities.

Table 3.8-2 Process-Product Mapping for HSI in Phase E

SEE Process	SEE Process Title	Key HSI Activities	Major HSI Products Per Milestone
2	Technical Requirements	HSI team evaluates final values of HSI TPMs	DR: HSI TPM Final Report
8	Product Validation	Analyze Flight Test Objective data and report on the outcome	PFAR: HSI input to Flight Test Reports PFAR: HSI models validated based on flight data
15	Technical Data Management	HSI Team produces HSI Technical Lessons Learned	DR: HSI Lessons Learned
16	Technical Assessment	Analyze operational aspects that affect human users/maintainers to determine where the system is fully successful or needs improvement	PLAR, CERR, PFAR: HSI lessons learned and technical reports on human-system operations

The Phase E milestones ensure user/maintainer safety, health, and performance, and capture HSI knowledge gained over the course of the P/P.

HSI system operational procedures are validated and documented for **SEE 8** and assessed for optimization for **SEE 16**. The P/P is also assessed for satisfactory completion of design objectives. TPM results (**SEE 2**), HSI validations, and design/operational feedback being captured documented and captured as lessons learned for **SEE 15**.

3.9 Phase F: Closeout

3.9.1 Phase F Objectives

The Closeout Phase, Phase F, is the final phase of the NASA SE process or life cycle. The role of the HSI team in Phase F is similar to that of Phase E, primarily ensuring that lessons learned are collected and fed forward into future P/P. These lessons may impact the revision and development of future requirements or standards. They may suggest new design opportunities or reveal previously unquantified limitations of systems or their operators. There may be data that has been catalogued throughout a design's operational missions that were to this point unreleased, and now is a key opportunity for the HSI team to review this information.

Phase F NASA Systems Engineering Goals

- Implement decommission/disposal
- Analysis of data
- Analysis of returned samples

In Phase F, the HSI team is focused on achieving the safe and successful decommissioning and disposal of the mission system, while documenting the knowledge gained in its development and operations. Successful decommissioning of the system is the end state for the P/P.

Phase F HSI goals and success criteria are mapped to relevant the milestones in Table 3.9-1.

The Phase F milestone entrance and success criteria are provided in NPR 7123.1B as follows:

- Table G-18 - Disposal Readiness Review Entrance and Success Criteria.

Table 3.9-1 Goals and Success Mapping for HSI in Phase F

Milestone	HSI Goals	HSI Success Criteria
Disposal Readiness Review (DRR)	Provide HSI support to the safe and successful decommissioning of the system. Capture final HSI Technical Lessons Learned. Archiving HSI data from P/P.	HSI aspects of system decommissioning and disposal are incorporated into the P/P plan. HSI data and lessons learned are captured for archiving.

3.9.2 Phase F Process and Products

The HSI team supports the system decommissioning and disposal process, where human operations and interactions with hardware/software continue to be essential to the achievement of P/P goals. The HSI team closes out its P/P work by documenting information that characterizes the value added by HSI to the P/P, and by transmitting this information to P/P and institutional organizations for archiving and re-use on future P/P.

HSI continues to provide uniquely valuable products during this final phase, by retrospective analysis of the P/P results and through HSI input to the human-system aspects of the decommissioning process itself.

Table 3.9-2 defines HSI products resulting from these activities. The Disposal Readiness Review (DRR) confirms the readiness for the final disposal of the system assets. At this time, the HSI team may provide human-system inputs to the decommissioning and disposal planning.

Table 3.9-2 Process-Product Mapping for HSI in Phase F

SEE Process	SEE Process Title	Key HSI Activities	Major HSI Products Per Milestone
N/A	N/A	HSI team provides input to the system decommissioning plan	DRR: HSI input to the decommissioning and disposal plan

The Phase F continues the Phase E system documentation activities. This phase may also overlap with early-phase activities for follow-on system designs that mature, replace, further optimize, or extend developed system capabilities.

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4.0 HSI PLANNING AND EXECUTION

The planning and execution of HSI is ultimately the responsibility of the P/P manager, but is carried out through the P/P's SE process, led by delegated practitioners skilled in HSI. The systems engineer is skilled in the art and science of balancing organizational and technical interactions in complex systems but may not have experience in human-centered design or in HSI disciplines. Gathering together the appropriate human-centered domain and subject matter experts is essential for project success in HSI. Since the entire P/P team is involved in implementing the SE approach, everyone should recognize some responsibility for aspects of HSI's planning and execution to ensure P/P success. The HSI practitioner must communicate effectively with the entire P/P team in order to generate the necessary level of HSI engagement. To support that outcome, this section provides an in-depth look at skills and management approaches required to execute HSI processes and produce HSI products.

4.1 NASA HSI Products

As evident in section 3, tangible products from the HSI effort are necessary for communication and engagement with the P/P. Three guiding documents are the ConOps, SEMP, and the HSI Plan. Other HSI products may also be documented in the HSI Plan. Not all P/Ps will have the same set of products.

The ConOps is developed early in Pre-Phase A, describes the high-level concept of how the system will be used to meet stakeholder expectations, usually in a time-sequenced manner. It describes the system from an operational perspective and helps facilitate an understanding of the system goals. The ConOps is essential for human integration, as it defines the operational, maintenance, transport, and other user interactions that HSI domain stakeholders will have with the system. Section 4.4.2, Developing a Concept of Operations (ConOps), provides information useful for composing the ConOps to address HSI considerations.

The SEMP is the primary, top-level technical management document for a P/P. It is developed early in the life cycle, and is updated at significant milestones throughout the P/P life cycle.

The HSI Plan—a practice in NPR 7123.1B, is a clearly identified section within the SEMP or a stand-alone HSI Plan document, depending on the size and scope of the P/P. In order to manage HSI throughout the life cycle of a program, a comprehensive HSI Plan or HSI portion of the SEMP should include strategies to address issues related to the development of HSI requirements. A detailed discussion of the HSI Plan content is provided in section 4.4.1, Writing the HSI Plan.

HSI requirements are an important HSI product. Requirements are the ultimate tool for impacting system design and performance, but they often also have cost and schedule implications. HSI requirements ensure that the human is adequately considered during system design. HSI requirements are developed, integrated, interpreted, and verified with support from parties responsible for HSI, from SE personnel, and from discipline experts in each HSI domain. Development considerations for HSI requirements are covered in section 4.4.4 of this document.

A P/P's HSI approach should be tailored to include use of various products and tools as appropriate. Note, however, that HSI data is often integrated with other data in a standard

product of the P/P and not uniquely an HSI product. Any product can have HSI implications; human considerations naturally occur as part of effective capability-based SE.

Section 4.2, Scaling and Tailoring HSI to Program/Project Size, provides HSI product guidance for various P/P sizes.

Sections 4.3 through 4.6 of this guide provide additional detail on the key HSI products listed in this section and more (e.g., planning, tailoring for size, metrics). The text also covers a variety of important HSI products resulting from human-centered trade-offs, usability assessments, and training programs. These products are put into the context of the NASA Life Cycle in Chapter 3.

4.2 Scaling and Tailoring HSI to Program/Project Size

Tailoring of the size and scope of the overall program management and SE efforts for a particular P/P will be performed by the program management and SE team leads. The HSI effort required of a project should be similarly scaled and tailored to fit a P/P's size, budget, mission, and scope. The HSI practitioner should work with the program management and SE teams to scope the HSI effort, and the HSI practitioner should strongly advocate for approval of an HSI level of effort that will successfully serve the P/P's outcomes.

An initial focus of tailoring HSI to P/P size is to determine whether a full or abbreviated HSI Plan is needed. Also, the HSI practitioner should work with the program management and SE teams to determine if the HSI Plan will be a standalone document or contained within the SEMP. These HSI Plan determinations are based on assessing factors such as a) the extent to which humans are involved with the system under development, b) the size of the P/P, c) the project category (per NPR 7120.5E, section 2.1.4), and e) P/P mission scope. If a P/P involves significant HSI, user/maintainer training, or new human-centered technology, for example, then a full HSI Plan should be initiated. In a smaller P/P or one that is similar to a predecessor system in the aforementioned respects, then an abbreviated HSI section within the SEMP may be sufficient as the HSI Plan. The HSI practitioner is cautioned against using the P/P budget as a primary consideration when determining HSI effort.

A checklist examining the P/P needs across all the HSI domains can assist the HSI practitioner to appropriately set the scale and content of the HSI effort. A sample checklist is provided in this guide as Appendix B, Sample HSI Implementation Planning Checklist. As soon as the HSI practitioner assumes HSI lead responsibility for a system's development and acquisition, the checklist assessment should be initiated and documented in the HSI planning effort.

A simplified, notional list of P/P size characteristics is shown in Table 4.2-1, which can be used by the Practitioner to scale the HSI effort along the lines of the example activities and products shown in Table 4.2-2. These tables and their illustrated characteristics are intended as useful indicators, not requirements. It is not essential that all of the characteristics for P/P size be met to assign an overall size category. Generally, the HSI effort for a P/P should be sized and focused based on its most critical safety or human involvement characteristic(s).

Table 4.2-1 Characteristics of Program/Project Relevant to HSI Scaling

P/P Size	Human Safety	Human Involvement
Large-Scale HSI Effort	Category I <ul style="list-style-type: none"> • Significant Risk • Hazards Controlled, Monitored by humans • LOC/LOM risks managed • Human-rated Program • Life-sustaining equipment 	<ul style="list-style-type: none"> • Large and complex hardware/software systems • Tight coupling of human actions to critical system performance • Flight Crew involved with day-to-day operations; "lives in the product" • Ground crew, operators critical to success • Extensive training required
Medium-Scale HSI Effort	Category II <ul style="list-style-type: none"> • Modest risk, hazard controls • Supports Human-rated Program 	<ul style="list-style-type: none"> • Medium system complexity with a number of hardware/software subsystems • Moderate coupling of human actions to critical system performance • Crew essential to mission success; "works with the product" • Ground crew, operators essential to success; some automation (Robotics program)
Small-Scale HSI Effort	Category III <ul style="list-style-type: none"> • Low risk, hazards • Supports Human-rated Program 	<ul style="list-style-type: none"> • Simple systems with small number of hardware/software components • Loose coupling of human actions to critical system performance • Crew involved with some aspects; "uses the product" • Ground crew, operators less involved; automation use to reduce human interactions • Some training required

Table 4.2-2 HSI Plan Activity and Product Tailoring

Product or Activity	Large-Scale HSI Effort	Medium-Scale HSI Effort	Small-Scale HSI Effort
Early Planning			
ConOps	Standalone Doc(s)	Possible Standalone Doc	Part of Project Docs
HSI Plan	Standalone Doc	Part of SEMP	Part of Project Docs
HSI Team	Required*	Recommended	As needed
Design Planning			
HSI Requirements	Standalone Doc	Strong Effort	Modest Effort
Human-centered design	Significant Effort	Strong Effort	Modest Effort
Human-in-the-Loop Prototyping, Evaluation	Significant Effort, Iterative	Strong Effort	Modest Effort
Production and Operation			
Human-in-the-Loop Verification, Training	Required	Supported	Desireable
Validation Activities	Supported	Supported	Desireable
Operational Monitoring	Supported	Supported	As needed
Lessons Learned	Supported	Supported	Desireable

* NPR 8705.2B controls formation of the HSI Team

HSI at the End Item Level

HSI approaches can also be applied to individual end items (e.g., exercise equipment, tools) using the guidance in this section. Device size is irrelevant; human interaction is the key. The effort may be highly constrained for limited resources when scaled to this level, but the HSI key concepts still apply: “human considerations” are fundamental to HSI, no matter how big (or small) the project. Crew time is a highly constrained resource and each device can have a significant impact: consider both local (device) and global (system) interactions.

It should be noted that a P/P will often produce a system that contains within it lower level components, units, or elements that are less human-oriented and so may be treated with less attention to HSI techniques. For example, a structural component not exposed to human interaction may have very few HSI requirements that drive its design. The HSI team, including all its domains, should be involved in this assessment of what is important for the HSI effort to cover and at what depth. A role of the HSI Plan is to identify those areas where HSI techniques are required and to document the approaches to be taken.

4.3 Planning the HSI Effort

HSI planning begins at the earliest outset of a project/P—i.e., during (or even before) Pre-Phase A. Besides learning about the goals and intent of the P/P, the HSI practitioner should begin focusing on putting in place the people, plans, processes, metrics, and products that will yield life cycle benefits to the particular program or project. These HSI preparations are documented in the HSI Plan. Section 4.1, NASA HSI Products, describes how the HSI Plan relates to other HSI products and section 4.4.1, Writing the HSI Plan, provides guidance on writing the Plan.

4.3.1 Developing the Plan

The practitioner should plan NASA-led HSI activities, requirements, and team structure, as well as understand the role that any prime contractor engaged on the program or project will perform, particularly in terms of HSI and HSI deliverables. A clear vision of HSI efforts needed to support the particulars of the P/P is critical to developing a comprehensive, integrated HSI approach, delivering a return on HSI investment, and producing a system that will meet user needs from human-systems and operations standpoint.

4.3.2 Organizing the HSI Team

The HSI practitioner should assess the types of human-oriented system design expertise needed and plan to form a team that is appropriately composed and organized to fulfill the HSI plans, activities, and products necessary for the particular P/P's life cycle. Composition of the team is determined by the scope, nature of the system and its operational mission, and the types of human/system design challenges anticipated. The lead HSI practitioner is the person the P/P management identifies to lead the HSI effort and report to program management and SE process managers. This lead HSI practitioner assists P/P management in assessing HSI personnel needs, HSI personnel timing, and critical early-phase HSI efforts, based on the P/P's scale, mission, budget, and scope. The HSI lead for the P/P plans and negotiates the necessary institutional SME resources as early as practical in order for the HSI team to form and create an implementation plan prior to early-phase activities, such as requirements definition, system architecture development, and functional decomposition. The HSI Plan captures appropriate HSI team information, intra- and inter-team roles and responsibilities, staffing agreements, and HSI team objectives.

For programs or projects that require large scale HSI efforts, extensive institutional resources are dedicated to HSI. A comprehensive, knowledgeable HSI team is essential to mission success, particularly in large scale P/Ps. For small-scale HSI efforts, identifying the scope of the HSI effort is equally as critical since the smaller HSI team size requires precise planning of a resource-constrained SME skill set. Understanding the domain expertise required for a particular program or project allows the practitioner to sharply focus the available HSI resources on the most critical HSI efforts documented in the HSI Plan.

4.3.3 Balancing Institutional Goals with Programmatic Goals

HSI work is closely associated with NASA's need to develop and operate systems in affordable and cost-effective ways, while also controlling safety and mission success risks to acceptable levels that are appropriate to each application.

Program authorities such as NASA mission directorates are chartered to create capabilities and to conduct missions, and they accomplish this via their funded programs and projects. They are motivated to take on additional risk at times in system development and operation in order to maximize programmatic accomplishments. The institutional authorities—i.e., Agency technical authorities—are charged with evaluating the risk posture of each program and project in order to ensure that the degree of risk to safety and mission success is well understood and is appropriately balanced against the need to accomplish the programmatic goals. This healthy tension is inherent to NASA's governance model.

The HSI practitioner should recognize that while working within the P/P, the HSI team also is closely associated with technical authority stakeholders from the NASA institution. For example, the HMTA promulgates human system standards at the Agency level (NASA-STD-3001) that are applicable to human space flight programs and projects. More broadly, the SMA TA and ETA provide standards applicable to all Agency programs and projects. The HSI effort creates one of the balance points between institutional standards and programmatic goals, as illustrated by the Constellation Program (CxP) example below.

Human Systems Integration in Practice: Constellation Lessons Learned

NASA's Constellation program (CxP) provided a unique test bed for Human Systems Integration (HSI) as a fundamental element of the Systems Engineering (SE) process. Constellation was the first major program to have HSI mandated by NASA's Human Rating document. The CxP Human Systems Integration Group (HSIG) was a part of the Systems Engineering and Integration (SE&I) organization within the program office, and existed alongside similar groups such as Flight Performance, Environments & Constraints, and Integrated Loads, Structures and Mechanisms. Although the HSIG successfully managed, via influence leadership, a down-and-in Community of Practice to facilitate technical integration and issue resolution, the program structure did not provide the necessary top-down authority to drive integrated design. Involvement of and coordination with NASA Technical Authorities was a key aspect of the HSIG in development of a human-rated system design.

4.3.4 Identifying Human-Centered Trade-offs

Instituting HSI requirements in system development and acquisition programs lead to the inclusion of human-centered considerations in trade studies and trade-off evaluations. There are a variety of measures that can be employed to set up an effective trade-off that directly or indirectly affects cost. But other equally valuable criteria can be established per the goals of the P/P that are not cost-based, but values-based.

The benefit to a P/P of implementing HSI is based on the value subscribed by the stakeholders. If the stakeholders place a high value on a design that reduces operational costs and optimizes human efficiency, then the engineering team can establish criteria to drive the trade space. Reducing cost, in and of itself, is not always the top priority, but must be considered along with the other selected criteria.

The criteria will be tailored to the needs of the individual P/P trade-off, which can be performed at a system, element, unit, or component level as needed.

The primary purpose of this section is to encourage a wider range of criteria be considered when setting up the trade study or trade-off matrix. A few examples are provided in Table 4.3-1, Example HSI Trade Study Criteria, and Table 4.3-2, HSI Trade-Off Examples.

Table 4.3-1 Example HSI Trade Study Criteria

Trade Study	Example Criteria
Crew-operated Instrument or Medical Device (multiple sources)	<ul style="list-style-type: none"> • Portability: attach points, handles, size, cabling • Power: battery management logistics, cabling, heat, noise (fans), interface availability and type • Calibration: crew time, periodicity, complexity, accuracy • Complexity to operate (subjective assessment) • Display readability
Net Habitable Volume (multiple designs)	<ul style="list-style-type: none"> • Proposed Crew size > consumables, life support, etc. • Proposed Design Reference Mission (DRM) timeline • Vehicle size constraints

Table 4.3-2 HSI Trade-Off Examples

Example Topic	Trade-Off	Considerations (HSI)
Hand-held Device	Portability: attached power cable vs. replaceable batteries	<ul style="list-style-type: none"> • Battery Logistics cost • Crew time impact for replacing batteries • Battery run time
Line/Orbital Replacement Unit (LRU/ORU)	Testability: built-in diagnostic self-test vs. ready spare on-orbit	<ul style="list-style-type: none"> • Mass, power, complexity, comm. for added capability • MTBF; R&R periodicity • MTTR; R&R on-orbit time • Criticality of function
Emergency Egress and post-landing survival in sea states	Cabin temperature vs. acoustic noise vs. suit and vehicle design vs. crew health and performance	<ul style="list-style-type: none"> • Vehicle constraints: battery life, communications, life support • Landing ConOps • Human Health constraints
Water Sampling Device Complexity	Crew time vs. cost of automated or autonomous system	<ul style="list-style-type: none"> • Cost of design • Crew time impact for repetitious operation • Design for back-up manual mode

For further examples, refer to the report “Human Systems Integration (HSI) Case Studies from the NASA Constellation Program” by Baggerman, Berdich, and Whitmore (2009).

For decision-making, establishing an exact cost is not as important as having a measurable metric that translates to cost. In this approach, the true cost is not actually calculated, but a cost-related metric is derived to “stand in” for cost. The cost-equivalent metric is used in evaluations or even requirements to produce desired outcomes in decision-making and design options. An example cost-equivalent metric can be found in section 4.4.5, Developing and Using HSI Metrics.

Another prime consideration for decision making is for the larger architecture-level trade-offs which can have a significant impact on LCC. These decisions must be made early in the project life cycle and validated with the other P/P stakeholder values, goals, and objectives. The range of choices is extensive but can include “moving the sliders” for such things as:

- Function allocation to hardware, software, and humans
- Autonomy
- Automation
- Redundancy, fault management architecture
- Engineering development tool choice (model-based, etc.)
- Risk tolerance for new technologies
- Operational environments and envelopes

The high-level architecture and programmatic decisions must take into account the level of involvement of humans in the system. Refer to NASA/SP-2010-576, NASA Risk-Informed Decision Making Handbook, for more details.

Some specific examples include crew time for select phases (set up, operation, tear down, maintenance), number of ground operator or hours, ease of access, ease of repair, ease of disposal, etc. These parameters are sometimes used for a comparative cost analysis in a trade-off study or as a “killer trade.”

Table 4.3-3 provides additional examples from each of the HSI domains.

Table 4.3-3 Cost-equivalent Criteria Examples for Decision Making

Criteria	Domain	Criteria Type	Units of Measure
Approach involves handling of hazardous material (yes or no?)	Safety	Go-No Go	N/A
Mean time to “turn around” crew capsule for next flight	Maintainability and Supportability	Weighted	Days (Incompressible)
Acoustic Noise (generated by item)	Habitability and Environment	Weighted	dB
Tool operation (task analysis) with range of motion constraints	Human Factors Engineering	Weighted	Workload Score
Quantity of user steps to execute a given activity	Operations Resource	Weighted	Steps or Person-Hours
Amount of training required for mastering a task (trainers plus crew time)	Training	Weighted	Person-Hours

LCC and trade studies are just two examples of HSI measures used in P/P designs. An additional discussion on HSI metrics can be found in section 4.4.5, Developing and Using HSI Metrics.

A case study overview from ISS is provided for additional emphasis.

Emergency Lighting Case Study

During ISS development, a requirement for emergency lighting was established, intended to provide module exit “pathway” illumination during a power outage. The original fielded solution, Emergency Egress Lighting System (EELS), failed to take into account the extensive crew time required to change out the batteries required to keep the system operational. Plus there was extensive logistics for flying up batteries. After many “lost” crew hours, ISS reconsidered, and a second design iteration produced a much more elegant, low-cost and low-impact solution: circular photo-luminescent (glow-in-the-dark) markers, the Emergency Egress Guidance System (EEGS).

In this case study, crew man-hours is used as a cost-equivalent measure. The potential solutions in the second, “experience informed” iteration considered the actual monetary cost of the battery logistics as well. All of the potential design solutions were compared to each other using both the cost-equivalent crew man-hours and the actual cost logistics metric. The selected solution is low-cost for both metrics.

4.3.5 HSI Focus on Commercial-Off-The-Shelf (COTS) Products

The Design Solution process (SEE #4) or trade studies performed as part of the Decision Analysis process (SEE #17) may identify potential Commercial-off-the-Shelf (COTS) solutions that are viable candidates to meet the need.

A increasing trend within P/P is the use of COTS hardware or software when possible in order to save cost and meet schedule. Though the use of COTS products can save time and money, COTS products also increase the need for HSI assessment and risk mitigation. Competing COTS products may initially appear functionally equal, but an HSI practitioner may identify significant differences or provide important selection criteria.

The initial HSI screening during COTS search is critical to identifying a product that will integrate into the flight mission and system. Besides the requisite form, fit, and function criteria, the selection criteria can include other HSI domain-related factors such as (as applicable):

- Vendor reputation and experience
- Product history and consumer reviews
- Replacement availability, second source options
- Product life cycle (time on market, time to obsolescence)
- Manufacturing process and materials
- Complexity of device or application
- Standards-based design

- Risk to cost and schedule
- Safety to crew, vehicle, and mission
- User interfaces
- Impact to crew task time and efficiency
- Workmanship concerns
- Preliminary environmental assessment (e.g., thermal, vibe, power)
- Suitability for function from HSI perspective

There are many factors in assessing “suitability” for operation of COTS equipment in space. Since COTS devices are designed and built for terrestrial applications, the engineer making the selection must often resort to comparative assessments between candidates, discussed in earlier sections, with prioritized criteria. There are complex questions that must be answered with the support of experienced domain experts and stakeholders. Since the COTS product is already designed, the features and functions may not be a “perfect match” for the new space application. For example: Is it better to have a unit with additional features beyond functional need, or one that meets needs and is simple to operate? Will/can the unit be operated by a suited crewmember? Are the power, data, and physical interfaces suitable for the intended environment and workspace? Is the device labeled properly? Are special tools required to service the item, if required? An evaluation checklist should be developed that includes HSI criteria for each trade study/trade-off being conducted.

From a human safety perspective, engineer is advised to “look inside” the article to ensure proper workmanship and no prohibited parts or materials. Early testing of the COTS item is also advised in order to ensure expected function, quality, and protection of the project schedule if something goes awry. The engineer is strongly advised to work with domain experts and check “the rules” of the certifying authority for use of COTS on the P/P. All COTS items should be identified in design reviews and design documentation to allow visibility to regulating authorities (e.g., NASA Center Chief Engineer Office, electrical, electronic, and electromechanical [EEE] parts team). It is also recommended to consider developing a risk to the project for use of COTS.

4.3.6 Implementing HSI in Incremental Development

HSI Practitioners may be tasked to apply HSI goals to life cycle processes that have been tailored to the considerations of a specific P/P. In many cases, the outcome will be an incremental development model that produces the system’s initial capability early, followed by iterative cycles of feature development and product refinement. HSI is traditionally iterative in nature, as a key practice is the establishment and maintenance of communication and feedback loops between designers and HSI domain stakeholders.

In an incremental development environment (e.g., Agile software development), phases may be distinct or may overlap. They may also be plan-driven from a mature set of initial requirements, experience-driven based on experiences gained from interaction with the initial capability system, or a combinations of both. The goal of incremental development is to decompose the

development effort into smaller, manageable, and deliverable development of useful and high-quality products. By developing in increments, the systems gain maturity through continuous integration, validation, and verification, and development teams gain flexibility through early identification of risks and defects, and early incorporation of end-user feedback.

To balance HSI's objectives of early stakeholder engagement and focus on human-centered design with the flexibility and fluidity of an incremental design approach, practitioners and teams are required to be cohesive, communicative, and committed to meeting customer expectations. An iterative design may use swift-moving processes, but the primary focus is ultimately to design the system that the customer needs within the P/P constraints. NASA projects require rigorous attention to safety as a design consideration essential to mission success. Successful incremental design environments within NASA have tailored design processes to the NASA culture, creating hybrid life cycle models that combine elements of incremental development with more traditional, plan-based development to provide customers visibility into design considerations for safety, operability, and cost effectiveness.

In addition to processes for developing high quality systems, system usability processes are essential for ensuring stakeholder buy-in and mission success. Usability analyses and usability SMEs help mature early stage system functionalities into later stage design optimizations. This allows methods based on producing early hardware/software components to integrate the human during the complete development effort while consistently influencing design refinements throughout the life cycle.

Appendix C.6 provides an example of a successful implementation of an incremental design method (Agile) within the context of a NASA program.

4.4 HSI Approach Execution

Implementation of an HSI approach requires development of various products, which guide the execution of the approach. Key skills to effectively implement HSI are integration of subject matter expertise and development of HSI products including ConOps, HSI Plan/SEMP, and HSI-based requirements. Early HSI efforts are leveraged in assessing training needs and usability. In addition, an effective approach utilizes metrics and lessons learned to gauge effectiveness and provide insight to future HSI implementations.

Throughout this guide, we describe how the HSI practitioner engages with the program/project to develop the HSI products, bring in experts for specific tasks, and support the entire life cycle. This comprehensive approach ensures that HSI is inherent in SE activities. The HSI practitioner is also a key participant in reviews (e.g., CDR) in order to detect problems hidden in a complex design. This is only accomplished by being immersively engaged with the development effort.

4.4.1 Writing the HSI Plan

The HSI Plan (HSIP in NPR 7123.1B) documents a systematic approach for applying HSI concepts to optimize total system performance (hardware, software, and human), operational effectiveness, and suitability, survivability, safety, and affordability. Depending on the scale and complexity of the HSI effort, the HSI Plan is captured as a part of project documentation, as a section within the SEM, or as a stand-alone HSI Plan document (see section 4.2). In order to

manage HSI throughout the life cycle of a program, the HSI Plan should include a detailed approach for incorporating the human requirements into all aspects of system development, training, operation, maintenance, and support.

The HSI Plan is written by HSI personnel to address issues resulting from HSI assessments of predecessor systems and/or previous system spirals and increments. The HSI Plan gives insight into points of HSI engagement and the associated effectiveness measures. The HSI Plan exists to document sound, human-centered development approaches from the human/system functional analyses performed during pre-planning activities through product verification and operations assessments. An outline of the HSI Plan is provided below. For more details, see Appendix A, HSI Plan Content Outline. Table 4.4-1, Guidelines for Development and Refinement of the HSI Plan, provides by-phase details on producing and maturing the HSI Plan.

HSI Plan Content Outline

- 1.0 Introduction
 - 1.1 Purpose
 - 1.2 Scope
 - 1.3 Definitions
- 2.0 Applicable Documents
- 3.0 HSI Objectives
 - 3.1 System Description
 - 3.2 HSI Relevance
- 4.0 HSI Strategy
 - 4.1 HSI Strategy Summary
 - 4.2 HSI Domains
- 5.0 HSI Requirements, Organization, and Risk Management
 - 5.1 HSI Requirements
 - 5.2 HSI Organization, Roles, and Responsibilities
 - 5.2.1 HSI Organization
 - 5.2.2 HSI Roles & Responsibilities
 - 5.3 HSI Issue and Risk Processing
- 6.0 HSI Implementation
 - 6.1 HSI Implementation Summary
 - 6.2 HSI Activities and Products
 - 6.3 HSI Plan Update

Table 4.4-1 Guidelines for Development and Refinement of the HSI Plan

Life Cycle Phase	Guidelines for Development and Refinement of the HSI Plan
Pre-Phase A Phase A	Develop the HSI Plan based on the results of functional analyses and derived human-centered requirements.
Phase B	Revise HSI Plan to reflect results of human, hardware, and software task allocation determination, system specifications, and source selection strategies and results.
Phase C	Identify potential human-related shortfalls and failures in human-system integration. Develop and execute mitigation strategies. Update HSI Plan to include latest system specifications, integration strategy, analyses of training and support requirements.
Phase D	Update HSI Plan to address issues related to system integration with training and support strategies. After evaluation, incorporate results of evaluations regarding usability, operability, and supportability of the system. Ensure testing is accomplished by operational users in operating conditions. Identify human-related shortfalls and failures in human-machine integration. After the Plan is updated, document lessons learned to prepare for the next iteration of design.
Phase E Phase F	These phases realize the execution of plans derived during the development and acquisition of the system (e.g., training plan, disposal plan, operational resources, survivability, etc.). This is another opportunity to collect data (e.g., habitability, usability, training, environment, safety, occupational health issues, etc.) and document lessons learned.

The HSI Plan will define and emphasize the HSI approach in each of the domains. By identifying areas of SME need, the HSI team captures rationale to size SME engagement and expertise to provide system optimization insight tailored to the specific P/P needs. It is particularly important for the HSI Plan to capture an understanding of roles and responsibilities, not only within the HSI team, but also for the HSI team's overall interaction with the larger program management and SE teams and with other (hardware/software) discipline teams. The HSI Plan outlines the discipline's approach to risk identification and mitigation and how the HSI team will integrate with and/or utilize the program's risk and mitigation processes.

A checklist can assist the HSI practitioner to plan and assemble the HSI effort. The HSI team can utilize the checklist to assist in the HSI planning and documentation. The checklist will lead the HSI team through identifying baselines for, and integration of, HSI domains. A sample checklist is provided in Appendix B, Sample HSI Implementation Planning Checklist. As soon as the HSI practitioner assumes responsibility for a system development and acquisition program, the checklist should be initiated and documented in the HSI Plan.

4.4.2 Developing a Concept of Operations (ConOps)

The ConOps document is an essential tool for all P/P and not just an HSI consideration. The ConOps document (or possibly multiple documents for a large program) provides guidance for development of the system; function allocations to hardware, software, and humans; stakeholder goals and "requirements," and much more. The document is a view of the system from the perspective of the user(s). The amount of architecture or "design solution" included in the ConOps is a matter of approach but is generally kept minimal so as not to limit creative design solutions.

The ConOps is also used to establish a standard to which the P/P can be “trued” by means of validation activities. The well-known SE “V” diagram must begin with the ConOps on the left side and ends with the validation of the entire system on the top right.

The guidance that the ConOps provides for the development of the architecture and plans dictate that the ConOps be created early in the P/P life cycle, starting in Pre-Phase A, and baselined in Phase A. The document is updated for major reviews and changes will impact many P/P documents.

Due to the inclusive nature and wide scope of the ConOps, inputs must be collected from a range of sources and experienced SMEs. Effort should be taken to hold reviews and disposition comments from relevant team members and stakeholders. Often the same personnel who create the ConOps document will become the HSI team, if required to be stood up per the Human Rating requirements document.

Function allocation is performed early in the develop life cycle, often in conjunction with the ConOps development activity. Table 4.4-2, Function Allocation Process, provides details on the process and some specific HSI activities to be conducted.

Table 4.4-2 Function Allocation Process

Function allocation Process	HSI Mapping for Resilience
Successively define what the system must do at lower levels	Ensure that lower-level definitions include the human functions
Translate high-level performance requirements into detailed performance criteria or constraints to define how well the system must perform	Include human performance requirements and constraints (e.g., operator workload and availability) relative to mission performance
Identify and define internal and external functional interfaces	Define adaptive user interface and system feedback and control requirements to optimize operator workload, provide context, status, time, and priority
Identify functional groupings to minimize redundancy	Resilient systems may include redundant functions – ensure functions are coordinated
Determine functional characteristics of existing components	Evaluate existing components in new contexts under a range of operating conditions
Perform trade studies to determine alternative functional approaches to meet requirements	Examine trade-offs with various levels of automation, and consider other HSI domains

(Ref: The Human Role in Resilience Engineering: Malleable Function Allocation, Matthew R. Risser for NDIA, October 2012).

4.4.3 Integration of Subject Matter Expertise for HSI Activities

Consideration of SMEs is a critical part of the early definition (e.g., ConOps) and design process (e.g., requirements and analyses). Table 1.6-1 lists the domain areas for HSI that will provide the needed skill base. Table 1.6-1 provides a sample listing of many areas of specific HSI expertise available from SMEs. The HSI practitioner holds the key to leveraging the depth of their knowledge and skills, by methodical integration across multiple HSI domains, using established SE techniques and additional techniques that are more specific to the HSI team.

The SMEs efforts include development of HSI requirements for the program or project, application of those requirements to the system, and involvement in verification of the system as meeting the requirements. Depending on the nature of the P/P, the SMEs also may engage in product development, evaluation, and validation efforts, including planning and execution of integrated system tests, demonstrations, analyses, and ultimately, system operations.

Note that much of the SE-related human integration work has typically been performed by personnel who are SMEs in human factors engineering (HFE), they have learned to apply broad mission-system models that capture many aspects of HSI. These models are consistent with general SE and are applied by a skilled HSI practitioner.

The HSI practitioner's and team's integration effort lends appropriate, balanced weight to all SME inputs, without neglecting those that may be very specialized or that are more difficult to incorporate into design or operational methods, as illustrated in the example below.

Subject Matter Expertise Collaboration Example

Knowledge about **human deconditioning after extended exposure to weightlessness** is very specialized, and is the subject of multiple lines of research to improve the scientific and medical evidence base. Knowledge in this area is continually improving, and SMEs are the primary source of the most current insights.

An HSI practitioner may actively consult with SMEs in the Sensorimotor, Musculoskeletal, Cardiovascular, and HFE areas in order to provide a comprehensive, integrated view of deconditioning as a design influence on crew tasking at the time of spacecraft landing. This would provide the HSI practitioner with implications for the vehicle's design, to ensure crew health and safety risk was mitigated to the appropriate level to meet NASA human system standards.

4.4.4 Developing HSI-based Requirements

HSI Requirements are the ultimate tool for impacting system design and performance, but they often also have cost and schedule implications. HSI requirements ensure that the human is adequately considered during system design. HSI requirements are developed, integrated, interpreted, and verified with support from parties responsible for HSI, from SE personnel, and from discipline experts in each HSI domain. HSI requirements may come from standards, but they also are derived from the ConOps via functional analysis of the mission, scope, relevant HSI domains, and human risk mitigation.

Per NPR 8705.2B for Human Space Flight (HSF) P/P, the NASA-STD-3001 Vol. 1 and Vol. 2 standards provide the primary basis for HSI requirements, to mitigate health and performance risks to levels that are acceptable to the Agency. Additional standards including FAA-HF-STD-001, Human Factors Assessments in Investment Analysis: Definition & Process Summary for Cost, Risk, and Benefit, and MIL-STD-1472D, Human Engineering Design Criteria for Military Systems, Equipment, and Facilities, are applied in selected areas for human rating purposes and can be used for non-HSF P/P such as planetary robotic missions. For all space flight P/P, NASA-STD-5005D, Standard for the Design and Fabrication of Ground Support Equipment, provides the human integration standards for Ground Support Equipment (GSE). Additional standards from engineering domains, such as JSC-08080-2A, JSC Design and Procedural Standards, and from the safety domain, such as NASA-STD 8709.20, Management of Safety and Mission Assurance Technical Authority (SMA TA) Requirements, are related to the integrated set of HSI requirements. An example of a standard for software requirements for aviation is RTCA DO-178C, Software Considerations in Airborne Systems and Equipment Certification, and the companion documents.

Significant HSI guidance can come from other documents, such as institutional functionality and requirements to support each human space flight program. One such document is the Medical Operations Requirements Document (MORD), which is derived from NASA-STD-3001 Volume 1. Similarly, a Human Systems Integration Requirements (HSIR) document is derived from NASA-STD-3001 Volume 2. The HSI Practitioner must seek out the applicable document(s) for the program being supported. The documents mentioned generically above are typical for a human space flight program.

Each standard statement essentially defines a level of acceptable risk in a specific area. The standards are translated into program HSI requirements managed by the HSI team, to ensure traceability back to Agency standards, while creating information usable by the P/P in the SE, design, and operations teams. These requirements are sometimes very specific and quantitative because of the constraints imposed by human capabilities and limitations (e.g., specifics of maintaining health, performance), but they allow as much design/operations trade space as practical while protecting the human.

The HSI practitioner leads the effort to apply relevant Agency standards to the P/P, based on the DRMs and system architecture.

Developing HSI-based Requirements

As an example, for the Exploration Systems Development programs, the **Human System Integration Requirements** (HSIR) document was developed per the process outlined in this section. For the Commercial Crew Program (CCP) the HSI requirements were embedded into the CCT-REQ-1130 requirements document, per the program's desire to have an integrated set of all program-level requirements. In each case, the program DRMs were used to translate from Agency standards to requirements that were relevant to the program-specific system architectures.

4.4.5 Developing and Using HSI Metrics

HSI practitioners use metrics to estimate and track the effectiveness of the HSI implementation. Using quantitative metrics whenever possible allows HSI requirements to become measurable, which is necessary for effective implementation within the SE life cycle. To be effective, HSI metrics must be objective and verifiable, and further, must be validated against the system goals. Effective metrics can also reveal trends and identify where trade studies are needed.

Cost, schedule, risk, and performance are vital categories of metrics for characterizing success of HSI efforts. As noted earlier in this guide, key metrics that often measure HSI's success (or failure) on a program/project are operational resources (numbers of humans needed to make a system operational), personnel skill levels, and training.

Program-specific metrics may be developed to track elements of system development that have high levels of management visibility because they pose significant risk to budget, schedule, or mission success. These metrics are defined and tracked in the HSI Plan for reporting of program cost and value during system design reviews. The metrics in the HSI Plan mature during the project life cycle, improving the significance and merit of the metrics and showing trends in relation to program goals over time.

Depending on the nature of the program risk area, an HSI practitioner characterizes the risk using one or more of a variety of measurement methodologies. NASA/SP-2007-6105, section 7.8, details how (MOPs and MOEs can be used to establish and manage technical margins, thereby reducing development risk and increasing the probability of mission success. Similarly, a program may define programmatic and technical leading indicators (TLIs) to ensure proper progress and management. Definition, trending, and tracking of TLIs is detailed in NASA/SP-2014-3705, NASA Space Flight Program and Project Management Handbook.

Key Performance Parameters (KPPs) are metrics derived from overarching program goals, and are, therefore, applied to a particular scope. It is important to outline the goals and scope that will be served by a HSI KPP within the context of NASA in order to understand the life cycle impacts of HSI.

Key Performance Parameters (KPPs)

An example of a **KPP that can be applied to space systems is crew time**. One of the most challenging parts of defining a crew time KPP is in determining the threshold and objective values. ISS crew has had to go 30 days without a day off to accommodate necessary tasks; therefore, the objective value should be conservative to protect for unplanned activities (particularly safety critical activities) and maintain crew psychological health. The threshold value should likewise show significant improvement over the current ISS paradigm. If the baseline were to assume 2.5 out of 6 or 7 crewmembers' time would be devoted to maintenance, that yields the following:

Crew time required threshold value: No more than 40% of the crew work day hours should be devoted to task preparation, scheduled and preventative maintenance, training and procedure review, and check-out of on-orbit hardware and software systems. The objective value is set at 35%. Crew work day hours are defined assuming the standards regarding personal time, exercise, and sleep remain the same independent of the mission duration or destination, and is exclusive of the abovementioned activities.

An Astronaut's Experience on Mir:

"...I learned that it is impossible to separate habitability issues from productivity in scientific research. They're one and the same—from food, toilets, and a good layout of work station space."

- David Wolf, Space News, 22, March 16-22, 1998.

Consistent with this approach, a KPP could also apply to ground-based mission controllers as well as ground-based maintenance and logistics activities, expressed as a percentage of the human portion of the cycle time in mission control or in turn-around and launch preparation activities. These attributes are essential for providing the required program capabilities and contributing to improvement, effectiveness, achievability, and affordability as part of HSI SE activities.

4.4.6 HSI Verification and Validation

The HSI team focuses on achievement of functionally effective, maintainable systems that conform to the applicable human capabilities and constraints for each P/P. The success of the overall HSI effort relies on the HSI practitioner to prove that the end product meets the system design goals.

To verify that the system design meets the defined HSI requirements and validate that the system design meets the functional capabilities defined in the ConOps, the HSI practitioner uses a combination of human centered testing, modeling, and analysis. The design methods listed in section 2.5, HSI Team Application of Tools, Models, and Analyses, may be reapplied during the verification and validation (V&V) phases of the life cycle to prove that the design process has produced an appropriate end product. System verification requirements should also be written to include appropriate HSI-related evaluations.

Beyond verifying that system requirements have been satisfied, validation from an HSI perspective will focus on system optimization and risk mitigation. Optimally usable systems result from successful management of system integration with human components. Early testing and evaluation helps to mitigate functional risks by validating appropriate system functionality.

The scope of V&V activities largely depends on the nature of the DRM and system architecture. The relevant human characteristics may drive many aspects of human-to-system interface V&V (e.g., hardware and software interfaces). In a small-scale, simple project, the HSI requirements may focus on specific features of a hardware device that involve human visual interface (e.g., labeling or information displays) or manual interaction (e.g., switches and controls). In more complex P/P, this may extend to driving the nature of function allocations among many humans, hardware end items, and software configuration items. For a human space flight P/P, where a flight crew is dependent on system functionality to maintain their lives during a space flight mission, the HSI requirements will also drive complex system capabilities such as environmental control, life support, and habitation.

In each case, the system functionality must be characterized by the HSI team in the context of the overall P/P mission-system design. In some cases, functional optimization may be characterized by usability, determined as a likelihood of user errors when interacting with the system hardware/software or by assessing user satisfaction with the system. The outcome of successful HSI V&V efforts will be a system that is verified to meet system requirements, while validating that the design also conforms to the user needs in the context of the P/P mission (i.e., DRMs) as defined in the ConOps. Through HSI, the resulting end product system architecture mitigates user risk (i.e., human safety, health, and performance risk) to an acceptable level.

A key resource for achieving human certification of a spacecraft is NASA/TP-2014-218556. It is also a good reference for the many structured activities and products for human-centered design, in general.

HSI Example: Orion Usability

Human interfaces to modern complex systems typically include extensive **software-driven displays and controls**. HSI methods are critically important to produce safe and effective system operations through these software interfaces. In the Orion human space flight development program, a team of HSI personnel, focused in the HFE domain, performed dedicated analysis, standards development, HITL evaluations, and design refinement of many software display formats that will be used by flight crew to operate the Orion spacecraft. This activity demonstrated the value of HSI personnel as essential members of an early-stage, collaborative team including astronauts as primary users, software and avionics developers, and rapid prototyping experts. The products of this effort informed Orion software design work beginning in the pre-PDR stage of the program.

4.4.7 Training Domain Program Development

Knowledge derived from testing and evaluating usability can be extremely helpful in the development of system training. Often training plans are only considered after designs have been completed and are fixed. Considering training during earlier concept phases would make training more effective, as well as would ensure that designs selected during trade-off analyses have been evaluated to assess their impact on training. For example, will a particular design require specialized skills, unique methods, or repeated training sessions? The HSI team can boost training considerations early by including training resources in early assessments and providing the results of early functional analysis such as human task allocations and usability evaluations. These analyses may be provided to training groups for maturation and use in formal training.

HSI Plan documentation of the training approach should address training concepts and strategy in areas appropriate to the system. Training areas such as equipment familiarity, facilities, simulations, training aids, use of virtual systems, required skills, task time constraints, and system access constraints are likely to apply to space systems.

An effective training program will address many of the following criteria:

- Allow for interactions between platforms through simulation and virtual exercises, and provide training realism to include a realistic environment, communications, and associated integrated systems.
- Embedded training capabilities that do not degrade system performance below threshold values nor degrade the maintainability or component life of the system.

- An embedded performance measurement capability to support immediate feedback to the operators/maintainers and possibly to serve as a readiness measure for the training personnel.
- Training logistics necessary to support the training concept (e.g., requirements for new or upgrades to existing training facilities).
- Provide concurrent capability with actual equipment and training devices and systems.

4.4.8 Capturing Lessons Learned for Future HSI Activities

As a NASA discipline, HSI should strategically strive to identify consistent KPPs that may become common HSI currency across program/project types. Doing this will not only help clarify basic duties required of the HSI practitioner and of a successful HSI engagement, but having consistent metrics will help build a database that could demonstrate HSI's return on investment and that could help build a database of lessons learned for the practice of HSI.

Large and successful programs and/or projects typically become long-lived with extended operations phase(s), often with modifications performed to systems to extend original objectives and systems life, add new capabilities or mission objectives, and accommodate for unexpected behaviors. Extensive systems upgrades or refurbishment often start the SE process back at an early life cycle phase, usually Pre-Phase A. And, of course, the startup of any entirely new program or project begins at Pre-Phase A. The HSI practitioner can use the HSI Plan to document specific HSI goals that are based on lessons learned to ensure those goals are given their proper significance to influence design.

An important piece of information to bring to any Pre-Phase A (or other early phase in the life cycle) is lessons learned from the operation of the original system or, in the case of new starts, the operation of similar, legacy systems. The lessons learned capture system may be provided as an institutional resource or as a knowledge capture system provided for all program/projects by a NASA center. If a relevant lessons learned system is not able to inform a program/project, the management team must endeavor to perform a literature search to identify applicable lessons learned, a time-consuming and often unsatisfying process.

Having an active knowledge-capture system running during the operational phases of NASA systems requires resources, strategic thinking, and persistence. Additionally, to enhance its usefulness, an ongoing lessons learned capture system should have guidance available to facilitate its use by new designers who may not be aware which lessons are best suited to apply.

As a best practice, engineers should invest time to query any available program/project knowledge capture systems for lessons learned applicable to their design challenge. Since it is impractical to learn "everything," engineers are by default obliged to rely on specialists and experts to avoid the pitfalls and capitalize on previous successful implementations.

Capturing Lessons Learned for Future HSI Activities

“Only a fool learns from his own mistakes. The wise man learns from the mistakes of others.”

— [Otto von Bismarck](#)

For HSI practitioners, strategically investing in and utilizing knowledge capture systems carries unique challenges given the large volume of previous work that must be leveraged in order to “insert” humans into space system design. However, it should always be remembered that unlike other systems, the HSI practitioner does not have the option to “redesign” the human to fit the system, but must understand the intricacies of building a product for designed interaction of the human element with every aspect of the system throughout its life cycle.

Crew Comment Database

The ISS Program has implemented a **Crew Comment Database**, which can be searched for helpful comments from crew regarding a specific tread, device, procedure, etc. The reports from this database are a good source for lessons learned for new designs, or for the “extended Ops” phase where changes need to be made to the existing hardware to meet new mission objectives. (*Contact the ISS Program Office at JSC.*)

4.4.9 Life Cycle Cost Effect of HSI

As previously stated, a primary goal of HSI is to reduce overall P/P cost. HSI practitioners use the tools and techniques described in this guide not only for effective human-system design but also for cost avoidance in areas of HSI. Though overall system safety, effectiveness, and efficiency are goals of the HSI process, it was the potential for LCC savings that led to HSI becoming mandatory in the U. S. DoD and other federal agencies.

The NASA HSI practitioner should keep the cost avoidance aspect of HSI in view as the ultimate human element discipline integrator who must translate design decisions into P/P common currencies such as LCC, down time required for maintenance procedures, total system autonomy from logistics and resupply, etc. Human element life cycle operations generally manifest themselves as numbers of people, specialized skillsets, and the resources needed for training all users, maintainers, and operators.

It is not within the scope of this guide to provide a “how to” for calculating cost for P/P, but the effect of HSI on costs of established processes and P/P decision-making is important to consider. NASA/SP-2014-3705 is an excellent resource for P/P cost management guidance. See sections

5.5, Maturing, Approving, and Maintaining Program and Project Plans, Baselines, and Commitments, and 5.6, Cost and Schedule Analysis Work to Support Decisions, in the handbook. NASA/SP-2014-3705 also refers to the NASA Cost Estimating Handbook at <http://www.nasa.gov/offices/ooe/CAD/nasa-cost-estimating-handbook-ceh/>.

See “Cost Estimation of HSI” (Kevin Liu, 2010) for specific guidance including using the Constructive Systems Engineering Model (COSYSMO) tool.

From an HSI investment standpoint, the users of NASA hardware and software expect products that can be used safely and effectively to accomplish a given mission, with minimal errors and maximum efficiency. They also expect that the development community has addressed user needs and capacities as intrinsic to system effectiveness. These expectations may not be realized without a unified and integrated HSI investment.

As a P/P progresses through its life cycle, the cost of making design changes increases dramatically. (See Figure 1.4-2, Life Cycle Cost with Overlay showing “Locked-in” Costs, and the discussion in section 1.4 of this guide.) Future costs are “locked in” early in the course of decision-making; therefore, alternate design concepts should be iteratively evaluated for their LCC impact or failure to find more effective alternatives. Growth in operations phase personnel costs is particularly possible and even probable if not evaluated early. System designers must not assume that any design solution can be made usable by adding personnel, skills, and training. Rather, system designers must assume that these human resource assets are as limited as any other P/P asset. Costs can also increase from making assumptions about human performance that are not achievable or from not including HSI domain considerations in design trade analyses to appropriately bound out-year cost escalation in operations, maintenance, and logistics human element expenditures. Applying HSI processes should reduce LCC through emphasizing efficient human performance goals and operations during system design and development.

There are not many case studies that fully evaluate the impact of HSI to LCC on past programs or that fully evaluate the return on investment of applying HSI fully and effectively. This is because it is rare that the outcome of a program that implemented HSI can be compared to the outcome of an identical program that did not, thereby producing a controlled comparison. The true cost of a path not taken is difficult, if not impossible, to obtain. However, adding HSI-oriented alternatives to the SE hardware/software trade space can provide another means to positively impact and evaluate LCC through the SE trade study process. This is covered in detail in section 4.3.4, Identifying Human-centered Trade-offs.

Particularly in the earliest stages of a new P/P, the HSI practitioner may find it necessary to justify the value of providing targets for and tracking costs for the human elements required to make a system functional throughout its life cycle. Standing on requirements documents alone may not carry as much leverage as being able to cite examples and case studies where HSI makes (or could have made) a difference in the success (or failure) of a P/P to meet its stakeholders' expectations. Some examples of both positive and negative HSI case studies are provided in section 4.4.10.

4.4.10 HSI Case Studies

Appendix C is structured to provide several case studies, moving from negative examples in which P/P did not fully leverage HSI, to their detriment, to positive examples in which P/P implemented HSI to their benefit. The final case is of a future ideal state for a human Mars program. The following cases are cited in the appendix:

- C.1 - F-22 Hypoxia-Like Incidents: HSI Experience
- C.2 - Shuttle Ground Processing: HSI Experience
- C.3 - F-119 Engine: HSI Experience
- C.4 - Constellation Program: HSI Experience
- C.5 - HSI Ideal State for Future Large Scale Human Space Flight Program
- C.6 - Agile Development Brings New Challenges for Software Assurance at NASA

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APPENDIX A HSI PLAN CONTENT OUTLINE

A.1 HSI Plan Overview

The Human Systems Integration (HSI) Plan documents the strategy for and planned implementation of HSI through a particular program's or project's (P/P's) life cycle. The intent of HSI is:

- To ensure the human elements of the total system are effectively integrated with hardware and software elements,
- To ensure all human capital required to develop and operate the system is accounted for in life cycle costing, and
- To ensure that the system is built to accommodate the characteristics of the user population that will operate, maintain, and support the system.

The HSI Plan is program- or project-specific and is a NASA Systems Engineering (SE) applicable document per NASA Procedural Requirements (NPR) 7123.1B, NASA Systems Engineering Processes and Requirements. The HSI Plan should address:

- Roles and responsibilities for integration across HSI domains,
- Roles and responsibilities for coordinating integrated HSI domain inputs with the Program team and stakeholders,
- HSI goals and deliverables for each phase of the life cycle,
- Entry and exit criteria with defined metrics for each phase, review, and milestone,
- Planned methods, tools, requirements, processes and standards for conducting HSI,
- Strategies for identifying and resolving HSI risks, and
- Alignment strategy with the System Engineering Management Plan (SEMP).

The party or parties responsible for P/P HSI implementation—e.g., an HSI practitioner (or team)—should be identified by the P/P manager. The HSI practitioner or team develops and maintains the HSI Plan with support from and coordination with the project manager and system engineer.

Implementation of HSI on a P/P utilizes many of the tools and products already required by SE—e.g., development of a Concept of Operations (ConOps), clear function allocation across the elements of a system (hardware, software, and human), and the use of key performance measurements through the life cycle to validate and verify HSI's effectiveness. It is not the intent of the HSI Plan or its implementation to duplicate other SE plans or processes, but rather to define the unique HSI effort being taken to ensure the human element is given equal consideration to hardware/software elements of a P/P.

A.2 HSI Plan Content Outline

Each P/P-specific HSI Plan should be tailored to fit the P/P's size, scope, and purpose. The following is a sample outline for a major program—e.g., space flight or aeronautics:

1.0 Introduction

1.1 Purpose

This section briefly identifies the ultimate objectives for this P/P's HSI Plan. This section also introduces the intended implementers and users of this HSI Plan.

1.2 Scope

This section describes the overall scope of the HSI Plan's role in documenting the strategy for and implementation of HSI. Overall, this section describes that the HSI Plan:

- *Is a dynamic document that will be updated at key life cycle milestones.*
- *Is a planning and management guide that describes how HSI will be relevant to the P/P's goals.*
- *Describes planned HSI methodology, tools, schedules, and deliverables.*
- *Identifies known P/P HSI issues and concerns and explains how their resolutions will be addressed.*
- *Defines P/P HSI organizational elements, roles and responsibilities.*
- *May serve as an audit trail that documents HSI data sources, analyses, activities, trade studies, and decisions not captured in other P/P documentation.*

1.3 Definitions

This section defines key HSI terms and references relevant P/P-specific terms.

2.0 Applicable Documents

This section lists all documents, references, and data sources that are invoked by HSI's implementation on the P/P, that have a direct impact on HSI outcomes, and/or are impacted by the HSI effort.

3.0 HSI Objectives

3.1 System Description

This section describes the system, missions to be performed, expected operational environment(s), predecessor and/or legacy systems (and lessons learned), capability gaps, stage of development, etc. Additionally, reference should be made to the acquisition strategy for the

system—e.g., if it is developed in-house within NASA or if major systems are intended for external procurement. The overall strategy for program integration should be referenced.

Note that this information is likely captured in other P/P documentation and can be referenced in the HSI Plan rather than repeated.

3.2 HSI Relevance

At a high level, this section describes HSI's relevance to the P/P—i.e., how the HSI strategy will improve the P/P's outcome. Known HSI challenges should be described along with mention of areas where human performance in the system's operations is predicted to directly impact the probability of overall system performance and mission success.

HSI Relevance

Key points:

- Describe performance characteristics of the human elements known to be key drivers to a desired total system performance outcome.
- Describe the total system performance goals that require HSI support.
- Identify HSI concerns with legacy systems—e.g., if operations and logistics, work force, skill selection, required training, logistics support, operators' time, maintenance, and/or risks to safety and success exceeded expectations.
- Identify potential cost, schedule, risk, and trade-off concerns with the integration of human elements—i.e., quantity and skills of operators, maintainers, ground controllers, etc.

4.0 HSI Strategy

4.1 HSI Strategy Summary

This section summarizes the HSI approaches, planning, management and strategies for the P/P. It should describe how HSI products will be integrated across all HSI domains and how HSI inputs to P/P SE and management processes contribute to system performance and help contain life cycle cost (LCC). This section (or Implementation Summary, section 6 of this outline) should include a top level schedule showing key HSI milestones.

HSI Strategy

Key points:

- Identify critical program-/project-specific HSI key decision points that will be used to track HSI implementation and success.
- Identify key enabling (and particularly, emerging) technologies and methodologies that may be overlooked in hardware/software systems trade studies but that may positively contribute to HSI implementation—e.g., in the areas of human performance, workload, personnel management, training, safety, and survivability.
- Describe HSI products that will be integrated with program/project systems engineering (SE) products, analyses, risks, trade studies, and activities.
- Describe efforts to ensure HSI will contribute in critically important Phase A and Pre-Phase A cost-effective design concept studies.
- Describe the plan and schedule for updating the HSI Plan through the program/project life cycle.

4.2 HSI Domains

This section identifies the HSI domains (see Table 1.6-1, “NASA HSI Domains,” of this Handbook) applicable to the P/P including rationale for their relevance.

HSI Domains

Key points:

- Identify any domain(s) associated with human performance capabilities and limitations whose integration into the program/project is likely to directly affect the probability of successful program/project outcome.
- An overview of processes to apply, document, validate, evaluate, and mitigate HSI domain knowledge and to integrate domain knowledge into integrated HSI inputs to program/project and systems engineering processes.

5.0 HSI Requirements, Organization, and Risk Management

5.1 HSI Requirements

This section references HSI requirements and standards applicable to the P/P and identifies the authority that invokes them—e.g., the NASA Procedural Requirements document(s) that invoke applicability.

HSI Requirements

Key points:

- Describe how HSI requirements that are invoked on the program/project contribute to mission success, affordability, operational effectiveness, and safety.
- HSI should include requirements that influence the system design to moderate the work force (operators, maintainers, system administrative, and support personnel), required skill sets (occupational specialties with high aptitude or skill requirements), and training requirements.
- Define the program-/project-specific HSI strategy derived from NASA-STD-3001. Vol. 2, “NASA Space Flight Human System Standard, Volume 2: Human Factors, Habitability, and Environmental Health,” Standard 3.5 [V2 3005], “Human-Centered Design Process,” if applicable.
- Capture the development process and rationale for any program-/project-specific requirements not derived from existing NASA standards. In particular, work force, skill set, and training HSI requirements/goals may be so program-/project-specific as to not have NASA parent standards or requirements.
- Identify functional connections between HSI measures of effectiveness used to verify requirements and key performance measures used throughout the life cycle as indicators of overall HSI effectiveness.

5.2 HSI Organization, Roles, and Responsibilities

In this section roles and responsibilities for P/P personnel assigned to facilitate and/or manage HSI tasks are defined—e.g., the HSI Practitioner [and/or Team if required by NPR 8705.2B, Human-Rating Requirements for Space Systems w/change 4 dated 8/21/2012]. HSI Practitioner/Team functional responsibilities to the program are described in addition to identification of organizational elements with HSI responsibilities. Describe the relationships between HSI Practitioner/Team, stakeholders, engineering technical teams, and governing bodies (control boards).

5.2.1 HSI Organization

- *Describe the HSI management structure for the P/P and identify its leaders and membership.*
- *Reference the organizational structure of the program (including industry partners) and describe the roles and responsibilities of the HSI Practitioner/Team within that structure. Describe the HSI responsible party's relationship to other teams, including those for SE, logistics, risk management, test and evaluation, and requirements verification.*
- *Provide the relationship of responsible HSI personnel to NASA Technical Authorities (Engineering, Safety, and Health/Medical).*
- *Identify whether the P/P requires NASA- (government) and/or Contractor-issued HSI Plans, and identify the responsible author(s). Describe how NASA's HSI personnel will monitor and assess contractor HSI activities. For Contractor-issued HSI Plans, identify requirements and processes for NASA oversight and evaluation of HSI efforts by subcontractors.*

5.2.2 HSI Roles & Responsibilities

- *Describe the HSI responsible personnel's functional responsibilities to the P/P, addressing (as examples) the following:*
- *developing HSI program documentation;*
- *validating human performance requirements;*
- *conducting HSI analyses;*
- *designing human machine interfaces to provide the level of human performance required for operations, maintenance, and support, including conduct of training; and*
- *describing the role of HSI experts in documenting and reporting the results from tests and evaluations.*
- *Define how collaboration will be performed within the HSI team, across P/P integrated product teams, and with the P/P manager and systems engineer.*
- *Define how the HSI Plan and the SEMP will be kept aligned with each other.*
- *Define responsibility for maintaining and updating the HSI Plan through the P/P's life cycle.*

5.3 HSI Issue and Risk Processing

This section describes any HSI-unique processes for identifying and mitigating human system risks. HSI risks should be processed in the same manner and system as other P/P risks (technical, programmatic, schedule). However, human system risks may only be recognized by HSI domain and integration experts. Therefore, it may be important to document any unique procedures by which the P/P HSI Practitioner/Team identifies, validates, prioritizes, and tracks the status of HSI-specific risks through the P/P risk management system. Management of HSI risks may be deemed the responsibility of the P/P's HSI Practitioner/Team in coordination with overall P/P risk management.

- *Ensure that potential cost, schedule, risk, and trade-off concerns with the integration of human elements (operators, maintainers, ground controllers, etc.) with the total system are identified and mitigated.*
- *Ensure that safety, health, or survivability concerns that arise as the system design and implementation emerge are identified, tracked, and managed.*
- *Identify and describe any risks created by limitations on the overall P/P HSI effort (time, funding, insufficient availability of information, availability of expertise, etc.).*
- *Describe any unique attributes of the process by which the HSI Practitioner/Team elevates HSI risks to P/P risks.*
- *Describe any HSI-unique aspects of how human system risk mitigation strategies are deemed effective.*

6.0 HSI Implementation

6.1 HSI Implementation Summary

This section summarizes the HSI implementation approach by P/P phase. This section shows how an HSI strategy for the particular P/P is planned to be tactically enabled—i.e., establishment of HSI priorities; description of specific activities, tools, and products planned to ensure HSI objectives are met; application of technology in the achievement of HSI objectives; and an HSI risk processing strategy that identifies and mitigates technical and schedule concerns when they first arise.

HSI Implementation

Key points:

- Relate HSI strategic objectives to the technical approaches planned for accomplishing these objectives.
- Overlay HSI milestones—e.g., requirements definition, verification, known trade studies, etc.—on the program/project schedule and highlight any inconsistencies, conflicts, or other expected schedule challenges.
- Describe how critical HSI key decision points will be dealt with as the program/project progresses through its life cycle. Indicate the plan to trace HSI key performance measures through the life cycle—i.e., from requirements to human/system functional performance allocations, through design, test, and operational readiness assessment.
- Identify HSI-unique systems engineering processes—e.g., verification using human-in-the-loop evaluations—that may require special coordination with program/project processes.
- As the system emerges, indicate plans to identify HSI lessons learned from the application of HSI on the program/project.
- Include a high-level summary of the resources required.

6.2 HSI Activities and Products

In this section, map activities, resources, and products associated with planned HSI technical implementation to each system engineering phase of the P/P. Consideration might be given to mapping the needs and products of each HSI domain by P/P phase. Examples of HSI activities include analyses, mockup/prototype human-in-the-loop (HITL) evaluations, simulation/modeling, participation in design and design reviews, formative evaluations, technical interchanges, and trade studies. Examples of HSI resources include acquisition of unique/specific HSI skill sets and domain expertise, facilities, equipment, test articles, specific time allocations, etc.

When activities, products, or risks are tied to life cycle reviews, they should include a description of the HSI entrance and exit criteria to clearly define the boundaries of each phase, as well as resource limitations that may be associated with each activity or product (time, funding, data availability, etc.). A high-level, summary example listing of HSI activities, products and known risk mitigations by life cycle phase is provided in Table A-1:

Table A-1 HSI Activity, Product, or Risk Mitigation by Program/Project Phase

Life Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
Pre-Phase A	Concept Studies	<ul style="list-style-type: none"> ConOps (Preliminary—to include training, maintenance, logistics, etc.)
Phase A	Concept & Technology Development	<ul style="list-style-type: none"> HSI Plan (Baseline) ConOps (Initial) HSI responsible party(ies) and/or Team identified before SRR Develop mockup(s) for HSI evaluations Crew Workload Evaluation Plan Function allocation, crew task lists Validation of ConOps (planning)
Phase B	Preliminary Design & Technology Completion	<ul style="list-style-type: none"> HSI Plan (update) ConOps (Baseline) Develop engineering-level mockup(s) for HSI evaluations Define crew environmental and crew health support needs (e.g., aircraft flight decks, human space flight missions) Assess operator interfaces through task analyses (for, e.g., aircraft cockpit operations, air traffic management, spacecraft environments, mission control for human space flight missions) HITL usability plan Human-Rating report for PDR
Phase C	Final Design & Fabrication	<ul style="list-style-type: none"> HSI Plan (update) First Article HSI Tests Human-Rating report for CDR
Phase D	System Assembly, Integ. & Test, Launch & Checkout	<ul style="list-style-type: none"> Human-Rating report for ORR Validation of human-centered design activities Validation of ConOps
Phase E	Operations & Sustainment	<ul style="list-style-type: none"> Monitoring of human-centered design performance
Phase F	Closeout	<ul style="list-style-type: none"> Lessons Learned report

6.3 HSI Plan Update

The HSI Plan should be updated throughout the P/P's life cycle management and SE processes at key milestones. Milestones recommended for HSI Plan updates are listed in NPR 7123.1B, Appendix G.

HSI Plan Updates

Key points to be addressed in each update:

- Identify the current program/project phase, the publication date of the last iteration of the HSI Plan, and the HSI Plan version number. Update the HSI Plan revision history.
- Describe the HSI entrance criteria for the current phase and describe any unfinished work prior to the current phase.
- Describe the HSI exit criteria for the current program/project phase and the work that must be accomplished to successfully complete the current program/project phase.

APPENDIX B SAMPLE HSI IMPLEMENTATION PLANNING CHECKLIST

Human Systems Integration (HSI) requires planning across a wide range of human concerns, incorporation of lessons learned, and collaboration with subject matter experts (SMEs). Typically an HSI practitioner is responsible for planning the effort and arranging for collaboration and organization of an HSI Team, as required. This sample checklist is provided as a work aid for the practitioner to help expand the range of considerations. The checklist is organized by HSI domain topics. Caveat: This list is not intended to be comprehensive and the author cannot anticipate the particular specialties, environment, and human interactions of all P/P efforts.

B.1 Human Factors Engineering Analysis

- Does the concept design being discussed present any significant challenges, implications or constraints in the following areas:
 - Work/living space (especially number/size of berthing spaces)
 - System or display integration
 - Operability/Maintainability
 - Anthropometry/Ergonomics
 - Automation
 - Ambient environment
- Does the concept design require a new system interface or modification to an existing interface?
- Does the concept design require new forms of collaboration between humans and/or across systems?
- Are there new lighting conditions?
- Is there special gear required that may impact task performance?
- Are there personnel issues that may impact the system interface (Anthropometry)?
- Will new technology impact the interface (Automation, Aiding)?
- Does the concept design require the performance of additional tasks?
- Are there specific performance thresholds and objectives that impact mission outcome?
- Are there time limitations for task accomplishment?
- Are there accuracy requirements for task accomplishment?
- What are the physical constraints and workload placed on the crewmember by the system?

- What are the cognitive constraints and workload placed on the crewmember by the system?
- What is the system's ability to minimize the effect of environmental stressors on the crewmember?
- What is the system's ability to minimize the effect of mechanical (system-produced) stressors on the crewmember?
- What is the system's compatibility with crew life support and continuous operations?

B.2 Operations Resources Analysis

- Is there a legacy system to use as a personnel baseline?
- Do the personnel levels need to be constrained to the same level as the predecessor system?
- Will the personnel mix (crew, civilian, contractors) change significantly?
- Is there a mandate to optimize or reduce personnel resources?
- Have personnel resources been justified and/or modified to meet mission needs? How much could personnel grow before it would impact the life cycle cost (LCC) decision?
- If the personnel estimate is greater than resources, what is the resource sponsor's position regarding funding?
- Is there a need for increased experience?
- Is there a desire and/or need for unique combinations of skill sets, knowledge bases, and abilities?
- Are the skill sets, knowledge base, and abilities required by the new capability projected to be available in sufficient numbers in the timeframe required?
- Are there any known or projected changes to gender mix and/or cognitive abilities, physical characteristics, psychomotor skills, and/or experience level?
- Does the concept design take into account the projected personnel pool?

B.3 Maintainability and Supportability Analysis

- Approximately how many resources will it take to operate, maintain, train and support the full capability? (Full capability includes all operational and maintenance [local and remote] components.)
- What personnel estimate was used for the LCC assessment?
- How does the personnel estimate compare to current requirements?
- Will significantly new skill sets, knowledge bases, and abilities be required to support the capability?

- Have maintenance interval goals been identified? Have these been compared to reliability estimates to identify possible areas of risk?

B.4 Habitability and Environment Analysis

Acoustical Energy

- What are the noise levels for the system? Can they be reduced? What are the concerns for potential fielding location?
- Does this system meet the standards for steady state noise under the most severe operational and maintenance scenarios?
- Does this system meet the standards for impulse noise under the most severe operational and maintenance scenarios?
- Does this system meet the standards for blast overpressure under the most severe operational and maintenance scenarios?

Biological Substances

- Does the system configuration preclude exposure to microorganisms, their toxins and enzymes?

Chemical Substances

- Does this system produce or release any toxic substance during maintenance and operation?
- Are personnel exposed to unacceptable levels of toxic vapors, gases, or fumes?
- Are there any unacceptable levels of toxic gases in the crew environment when the vehicle is operating?
- Has each chemical or toxic material used in or with the system been identified in the health hazard assessment report?
- Does a hazard from exposure to_____exist?

Radiation Energy

- Are there hazards or potential hazardous exposures from ionizing radiation sources during operation, training, and maintenance?
- Are there hazards or potential hazardous exposures from non-ionizing sources during operation, training, and maintenance?
- Does the system contain any lasers detrimental to health?
- Has the system been evaluated for potential radiation health hazards?

Physical Forces

- Will this system produce any physical hazards?
- Is adequate protection provided to preclude trauma to the eyes or body surface during system operation or maintenance?
- Does the system meet vibration and shock requirements under all operational conditions?

Survivability

- Will the proposed capability increase the number/type (especially civilians and/or contractors) of individuals placed in harm's way?
- Does the concept design change egress systems requirements (if applicable)?
- Does the Concept of Operations (ConOps) for the proposed capability increase the need for improved personnel survivability features?

Temperature Extremes

- Does the system provide adequate heating, cooling, and ventilation under routine, severe, and emergency conditions?

Medical

- Have health problems identified with legacy/reference systems and components been addressed and abated in this system?
- What are disposal requirements? Will this process generate waste with special handling/disposal requirements?
- If Waste cannot be eliminated, then there will be additional training requirements for use, handling, storage and disposal.
- Does the system exhibit unacceptable conditions that might affect human performance capabilities (i.e., vision, olfaction, taste, hearing, reaction time, motor skills, strength, and cognitive skills)?
- Have required health services (i.e., nutrition, water, sleep, exercise, medical care [preventive, diagnostic, treatment]) been identified where applicable?
- Were required living conditions (i.e., personal hygiene, body waste management, crew quarters, mess, exercise area, recreation, trash, stowage, etc.) identified where applicable?

B.5 Safety Analysis

- Has a safety risk assessment been completed?
- Have safety risks concerning power sources been considered?
 - Electrical
 - Mechanical
 - Hydraulics/pneumatics
 - Chemical/explosive/propellants
- Look for safety risks associated with:
 - Exposed, moving equipment
 - Hazardous materials or by-products
 - High temperature devices
 - Vehicular movement/flight
- Ensure design requirement statements have been developed to address/prevent the impact of:
 - Catastrophic loss of system or crew due to failure/malfunction of component or procedural error/omission
 - Operational loss of system or disabling injury due to failure/malfunction of component or procedural error/omission
 - Loss of system effectiveness or injury due to failure/malfunction of component or procedural error/omission
- Are all trade-offs or impact issues looked at for their effects on all other HSI domain as well as system cost and performance requirements (e.g., excessive training and personnel capability requirements to compensate for system design weaknesses)?
- Are all functional, cost and performance data, as well as assumptions and other criteria, consistent with other analyses being performed on the system?
- Is the system safe for the crew/ground personnel to operate, maintain, repair, and support?

B.6 Training Analysis

- Was any part of the planned system functionality related to addressing human performance or training deficiencies?
- Could temporary or interim training be implemented to improve mission performance with current systems until the proposed concept design can be developed and deployed?
- Will deployment of the new capability change crew planning and decision-making?
- Will changes in either individual or team training be required to address the change to crew planning and decision-making?
- Has the crew been tested for preliminary workload estimates in visual, auditory, motor, and cognitive capacity? Do they meet requirements?
- If there is a desire and/or need for unique combinations of skill sets, knowledge bases, and abilities, are associated new training requirements feasible and reasonable?
- Will there be sufficient time to adjust and implement required changes to training?
- Have total system operational performance, support, or LCC objectives and thresholds been defined?
- Will the concept design change who is to conduct the training (Government, Contractor)?
- Will the concept design change where the training is conducted (Contractor Facilities, NASA Centers)?
- Will the concept design impact the timing of the training (Duration, Availability)?
- Does this affect cost estimates and LCC assessments?
- Will the concept design change the method of training used (classroom, computer-based, on-the job)?

APPENDIX C HSI IMPLEMENTATION EXPERIENCES

C.1 F-22 Hypoxia-Like Incidents: HSI Experience

Introduction and Summary:

The U.S. Air Force (USAF) F-22 program has experienced a number of operational incidents in which pilots experienced hypoxia-like symptoms during flight, with related symptoms post-flight. The USAF Scientific Advisory Board conducted an investigation and reported its findings in February 2012. The NASA Engineering and Safety Center (NESC) was then tasked to provide an independent analysis, and those findings were reported in August 2012. The following materials have been extracted from these reports and from NESC testimony given at a U.S. House Subcommittee hearing on this topic in September 2012.

It is clear from the investigative findings that human-systems integration (HSI) is a key technical area that was insufficiently performed during F-22 system development, resulting in the operational incidents reported by the flight crewmembers. The F-22 contractor-provided aircraft, the government-provided flight crew equipment, and the human pilot form a complex system that must operate in an integrated manner during flight. Emergent properties of the integrated system were found to be inadequate for proper support of critical aspects of human health and performance.

Sources:

United States Air Force Scientific Advisory Board Report on Aircraft Oxygen Generation, SAB-TR-11-04, 1 February 2012 (Approved for Public Release)

F-22 Life Support System (LSS) Independent Analysis, NASA Engineering and Safety Center, NESC-RP-12-00792, Version 1.1, August 23, 2012 (redacted FOIA release, 1 February 2013).

F-22 Pilot Physiological Issues, Hearing Before The Subcommittee On Tactical Air And Land Forces Of The Committee On Armed Services, House Of Representatives, One Hundred Twelfth Congress, Second Session, Hearing Held, September 13, 2012, U.S. Government Printing Office, 76-215 PDF, Washington : 2012, [H.A.S.C. No. 112-154] (publicly available).

Scientific Advisory Board Report, Synopsis of HSI Experience:

Background:

The F-22 was developed during a period of major changes in the Air Force acquisition process. The majority of the Department of Defense military specifications and standards were rescinded and the acquisition workforce was reduced in favor of increased industry responsibility. A

refined program management structure delegated many decisions to Integrated Product Teams (IPTs) for non safety-critical functions. These changes left major uncertainties as to what was an “inherently governmental responsibility.” Additionally, the program underwent several major restructures driven by cost and funding constraints, to include major reductions in the size of the F-22 program office.

During the early Advanced Tactical Fighter (ATF) development program, the precursor of the F-22 development, HSI analysts were chartered to focus on Manpower, Personnel, Training, and Safety. From 1989 to 1994, analysts from the Aeronautical Systems Division (ASD) HSI Office were collocated in the ATF Program Office. As a consequence of a heightened awareness of the manpower, usability, maintainability, safety, human effectiveness, and cost savings achievable by the application of human factor engineering methods, the analysts and program leadership were able to bring about changes representing different priorities and policies in program management decision-making. Engineering, human factors, manpower, personnel, training, and logistics were integrated.

Technical support of the efforts beyond the HSI technical capabilities embedded within the ATF Program Office came from the Air Force laboratories and the ASD engineering offices in areas including: crew systems, life support systems, oxygen generation, propulsion, workload management, training methods and simulators, cockpit controls and displays, and human factors engineering. As a result of the ATF contract efforts, the F-22 pilot was given advanced personal protective equipment; integrated sensors, controls and displays; stealth technology; and sustained supersonic cruise.

As the ATF moved beyond the fly-off phase and into the F-22 Engineering & Manufacturing and Development (EMD) phase, the acquisition policies had changed, diminishing the influence of proven military standards as well as national and international standards. Additionally, the workforce was downsized in response to acquisition reform initiatives. During the early 1990s, the ASD HSI Office work force was reduced to 21 positions. In 1994, prior to the developmental flight tests of the F-22, the HSI program office was disbanded due to funding and personnel reductions within ASD. The expertise required to perform the critical integration analyses became insufficient. Further, as a cost savings decision in the 2001 timeframe, the F-22 program chose to terminate a contractor-developed life support ensemble in favor of the government-developed life support equipment developed as a part of the “Combat Edge” ensemble. In view of the fact that the Combat Edge ensemble had been certified, specialized, and tested end-to-end, testing of that equipment for the F-22 was not deemed necessary.

The assessment by the Scientific Advisory Board, as documented in its report of February 2012, identified major shortfalls in the application of HSI principles, availability of appropriate breathing standards, and a comprehensive understanding of the aviation physiology implications of sustained operations at high altitude without a full pressure suit. The assessment of the environmental control system (ECS) and life support system development programs indicated a

major shortfall in the modeling and simulation of the system to determine performance under degraded conditions or in the presence of contaminants in the breathing gas.

Report findings included:

1. The F-22 on-board oxygen generating systems (OBOGS), Back-up Oxygen System (BOS), and Emergency Oxygen System (EOS) were not classified as “Safety Critical Items.”
 - The Life Support System (LSS) IPT eliminated the BOS to save weight.
 - The ECS IPT designed an Air Cycle Machine bypass to provide bleed air to the OBOGS in the event of an ECS shutdown.
 - The EOS was deemed to be an adequate BOS.
 - The ECS IPT decided to forgo the Air Cycle Machine bypass.
 - With an ECS shutdown, the pilot's flow of breathing air is cut-off thus requiring the pilot to activate the EOS to restore the flow of breathable air.
 - Interrelated and interdependent decisions were made without adequate cross-IPT coordination.
2. Over the past 20 years, the capabilities and expertise of the USAF to perform the critical function of HSI have become insufficient, leading to:
 - The atrophy of policies/standards and research and development expertise with respect to the integrity of the LSS, altitude physiology, and aviation occupational health and safety.
 - Inadequate research, knowledge, and experience for the unique operating environment of the F-22, including routine operations above 50,000 feet.
 - Limited understanding of the aviation physiology implications of accepting a maximum 93-94% oxygen level instead of the 99+% previously required.
 - Specified multi-national air standards, but deleted the BOS and did not integrate an automated EOS activation system.
 - Diminution of Air Force Materiel Command (AFMC) and Air Force Research Laboratory (AFRL) core competencies due to de-emphasis and reduced workforce to near zero in some domains.

3. Modeling, simulation, and integrated hardware-in-the-loop testing to support the development of the F-22 LSS and thermal management system were insufficient to provide an “end-to-end” assessment of the range of conditions likely to be experienced by the F-22.
 - Engine-to-mask modeling and simulation was non-existent.
 - Dynamic response testing across the full range of simulated environments was not performed.
 - Statistical analysis for analyzing and predicting system performance/risk was not accomplished.
 - Performance of OBOGS when presented with the full range of contaminants in the ECS air was not evaluated.
4. The F-22 life support system lacks an automatically-activated supply of breathable air.
 - ECS shutdowns are more frequent than expected and result in OBOGS shutdown and cessation of breathing air to the pilot.
 - The F-22 is the only OBOGS-equipped aircraft without either a BOS or a plenum.
 - The “OBOGS Fail” light on the integrated caution, advisory, and warning system (ICAWS) has a 12-second delay for low oxygen, providing inadequate warning.
 - When coupled with a rapid depressurization at the F-22’s operational altitudes, the “Time of Useful Consciousness” can be extremely limited.
 - The EOS can be difficult to activate, provides inadequate feedback when successfully activated, and has limited oxygen duration.
5. Contaminants identified in the ongoing Molecular Characterization effort have been consistently measured in the breathing air, but at levels far below those known to cause health risks or impaired performance.
 - Contaminants that are constituents of ambient air—petroleum, oils and lubricants, and polyalphaolefin—are found throughout the LSS in ground and flight tests.
 - OBOGS was designed to be presented with breathable air and not to serve as a filter.
 - OBOGS can filter some contaminants and there is evidence it may concentrate others.

6. The OBOGS was developed as a “fly-to-warn/fail” system with no requirement for initial or periodic end-to-end certification of the breathing air, or periodic maintenance and inspection of key components.
 - Engine bleed air certified “breathable” during system development.
 - OBOGS units are certified at the factory.
 - No integrated system certification.
 - No recurring Built-In Test, inspections, or servicing.
7. Given the F-22’s unique operational envelope, there is insufficient feedback to the pilot about the partial pressure of oxygen (PPO₂) in the breathing air.
 - Single oxygen sensor well upstream of the mask.
 - 12-second delay in activating the ICAWS when low PPO₂ is detected.
 - Inadequate indication of EOS activation when selected.
 - No indication of pilot oxygen saturation throughout the F-22 flight envelope.
8. The F-22 has no mechanism for preventing the loss of the aircraft should a pilot become temporarily impaired due to hypoxia-like symptoms or other incapacitating events.
 - Disorientation, task saturation, and/or partial impairment from hypoxia could result in loss of the aircraft and possibly the pilot.
9. The F-22 case study illustrates the importance of identifying, developing, and maintaining critical institutional core competencies.
 - Over the last two decades, the Air Force substantially diminished its application of systems engineering (SE) and reduced its acquisition core competencies (e.g., SE, HSI, aviation physiology, cost estimation, contracting, and program and configuration management) to comply with directed reductions in the acquisition work force.
 - By 2009, the Air Force had recognized this challenge and developed a comprehensive Acquisition Improvement Plan (AIP) and an HSI plan.
 - Although the AIP has been implemented, the HSI plan is early in its implementation.
 - A clear definition of “inherent government roles and responsibilities” is not apparent.

Respiratory Symptoms:

The Study Panel heard anecdotal reports that F-22 pilots frequently experience respiratory complaints within minutes to hours after completion of a sortie. The complaints were dominated by the occurrence of a mild to moderate non-productive cough unaccompanied by fever or other systemic symptoms. The Study Panel heard preliminary results of a formal survey of the F-22 and F-16 pilot community in which 65% of F-22 pilot respondents reported the occurrence of a cough during or shortly after some sorties, compared to 16% of F-16 pilot respondents. In addition, a significant number of F-22 pilots reported symptoms consistent with chest tightness. The temporal pattern of these respiratory symptoms does not appear to be consistent with acceleration atelectasis, a well-described entity in aviation medicine that is typically associated with the rapid onset of short-lived cough, chest tightness, or dyspnea.

Consequently, a formal clinical and epidemiological investigation of the respiratory complaints was recommended. Irritant effects of ozone, volatile organic compounds, and inorganic gases and fine particulates have been associated with dry cough and chest tightness. Immunological responses, including antigen induced asthma or hypersensitivity pneumonitis, may also be associated with symptoms of this nature.

Recommendations included:

Re-energize the emphasis on HSI throughout a weapon system's life cycle, with much greater emphasis during Pre-Milestone A and during Engineering and Manufacturing Development phases.

- Identify and reestablish the appropriate core competencies.
- Develop the capability to research manned high altitude flight environments and equipment, develop appropriate standards, oversee contractor development, and independently certify critical, safety-of-flight elements.

Outcome:

The assessment led the Scientific Advisory Board (SAB) Study Panel to make Findings and Recommendations to both mitigate identified risks in allowing the F-22 to return to flight and to provide the data necessary to identify the root cause(s) of these hypoxia-like incidents.

The SAB recommendations led to the NESC report, with relevant HSI results synopsized below.

NASA Engineering and Safety Center Report, Synopsis of HSI Experience:

The USAF and its contractors conducted investigations and a 4-month F-22 stand-down, without coming to a clear resolution of the issue. In May 2012, the USAF requested NASA assistance in the effort to determine the cause(s) of the hypoxia-like symptoms experienced by some F-22 pilots. NASA was requested to review the post-incident protocols and recommend enhanced procedures with a greater emphasis on analysis of the entire life support and cabin pressurization systems, and to review the investigative process, ongoing root cause analysis, and the F-22 LSS as a whole to determine potential vulnerabilities to the pilot.

The NESC led the effort with a team that included NASA flight surgeons, human factors experts, an Environmental Protection Agency (EPA) forensic chemist, an industry OBOGS expert, and NASA LSS engineers. The NESC team concurred that there was not a single root cause for the incidents, but a complex interaction of a number of factors, primarily:

1. High concentrations of oxygen (O₂) at lower altitudes can lead to absorption atelectasis.
2. The inevitable acceleration, which compounds the efforts of high O₂.
3. Restricted breathing due to the inappropriate inflation of the upper pressure garment (UPG) that not only prevented any relief of this atelectasis, but worsened the problem by causing rapid shallow breathing, and contributing to a reduction in cardiac output.
4. Contributions of uncharacterized F-22 LSS vulnerabilities, such as pressure drops across components in the cockpit.

The team found a number of issues with the systems providing support to the pilot. The LSS, ECS, and a government-furnished Combat Edge Aircrew Flight Equipment (AFE) are often treated as separate systems and controlled at the interfaces. The events experienced, however, are due to the complex interactions of these systems and the pilot. For example, pressure drops causing resistance to pilot breathing can be found across the interface between the LSS and the AFE and in the AFE components themselves. The unintended inflation of the UPG also restricts breathing. While the systems have no filter per se, the OBOGS and coalescer socks are filtering out contaminants. The OBOGS O₂ schedule is, on occasion, providing too much O₂, which exacerbates the situation. Contamination as a cause has been ruled out by the USAF.

The F-22 can be viewed as a system with many subsystems and components, each with varying degrees of direct and indirect influence on the sortie and on other components. In fact, it is a “system of systems.” The flight system can be viewed within the conceptual framework described by Technology-Human-Environment (THE) Model (Mauro, et al., in press). Adverse events during a flight can thus be seen as resulting from the interactions between the technology (i.e., hardware and software), the human, and the operational environment, within the context of the mission. There are two-way, three-way, and four-way interactions that should all be considered in any attempt to understand flight-related events. Given the dynamic nature of the

flight as a whole, and the complex nature of the human and the environment, the flight itself could be described as a complex system.

There are several aspects of complex systems that seem particularly relevant to the physiological events experienced by some F-22 pilots:

- *Complex systems are very sensitive to initial conditions; small variations in initial conditions can produce large variations in outcomes.*
- *Complex systems experience emergent phenomena, which cannot be predicted from the individual components (“the macro is different from the micro”; “the whole is greater than the sum of its parts”).*

The human is a complex system and as such, it is often difficult to predict how humans will respond to novel environments. For instance, NASA flight surgeons cannot predict which astronauts will develop space adaptation sickness. Similarly, the sleep pattern a given astronaut will develop in space cannot be predicted. Like space flight, flying the F-22 involves a novel environment that is different from the human body's natural environment.

Viewing the F-22 as a complex system allows the interpretation of many of the attributes of the physiological events as the results of complexity. Together, the model and the notion of complexity could provide some insight not only into understanding the events themselves, but also into understanding the limitations of the investigative approach taken in pursuit of root causes.

The F-22 physiologic events result from hypoxia. However, this is not the simple “hypoxic hypoxia” resulting from insufficient O₂ in the breathing air. It is far more complicated than that, and some basic understanding of aerospace physiology is necessary in order to properly understand the events. The F-22 pilot is exposed to a complex set of physiological interactions that on any day may combine to result in the cerebral cortex of the brain not receiving an adequate concentration of O₂. A particular pilot may compensate adequately on a particular day, whereas the various factors combine to produce overt symptoms in another pilot on another day.

Normally, in the lung, the blood flowing through the capillaries surrounding the alveoli (i.e., microscopic air sacks) is fairly evenly distributed throughout, such that almost all blood flowing past the alveoli is appropriately ventilated with air that carries an adequate amount of O₂. However, when a person is sitting or standing upright, the force of gravity will pull some of the blood to the bottom portions of the lung, much like water will seep to the bottom part of a sponge left sitting on a table. In the case of the lung, the combined weight of the blood, the upper portions of the lung, and the chest wall causes the small air sacs at the base of the lung to collapse. This is called atelectasis and, in normal circumstances, is only a very small part of the overall lung volume. Also, the blood flowing past these collapsed alveoli is not absorbing any O₂. The result of such blood flow is called “shunt.” On the other hand, the alveoli at the very top part of the lung have plenty of air being ventilated through them, but they have limited blood

flow; this is termed “dead-space” ventilation. Again, in normal individuals under normal circumstances, this accounts for a very small part of the overall ventilation of the lung.

If the inspired air has a high amount of O₂ in it (e.g., 60 percent or higher), it can cause the nitrogen to wash out of the alveolus, thus effectively absorbing most (if not all) of the gas in that alveolus. This will lead to collapse of the alveoli, and is known as “absorption atelectasis.” This phenomenon is worsened if the small airways leading to the alveoli are pinched off due to the weight of the blood and lung tissue, resulting in the trapped O₂ in the alveoli being completely absorbed by the blood. Absorption atelectasis can occur in conjunction with acceleration atelectasis (see below) if the inspired concentration of O₂ is high (>60 percent), in the context of pulling G's. Thus, too much inspired O₂, in the fighter environment, can ironically cause hypoxia.

One of the best ways of clearing areas of atelectasis in the lung is by taking in deep breaths, and by coughing. However, numerous observations have shown that this mechanism of clearing atelectasis in the F-22 community was inhibited because the UPG was inflating inappropriately. The result was that the inflated UPG could restrict the pilot's chest wall movement, thereby keeping the pilot from being able to take in a full deep breath. Without being able to take deep breaths, it is also more difficult to cough adequately. Therefore, the chest wall restriction resulting from inappropriate UPG inflation inhibited effective reversal (clearance) of the atelectasis in the F-22 pilots.

The results of the NESC study were briefed to a U.S. House Subcommittee as synopsized below.

Extract from NESC/C. Cragg Testimony to House Subcommittee:

The NESC assembled a team that included two NASA flight surgeons, two NASA human factor experts, an EPA forensic chemist, an industry oxygen generator system expert, and several specialized NASA LSS engineers.

In the course of this investigation, the team reviewed data from multiple sources, visited manufacturing sites and F-22 bases and held numerous discussions with knowledgeable personnel. The NESC team's findings and recommendations are based on this data and not on an exhaustive review of all F-22 documentation.

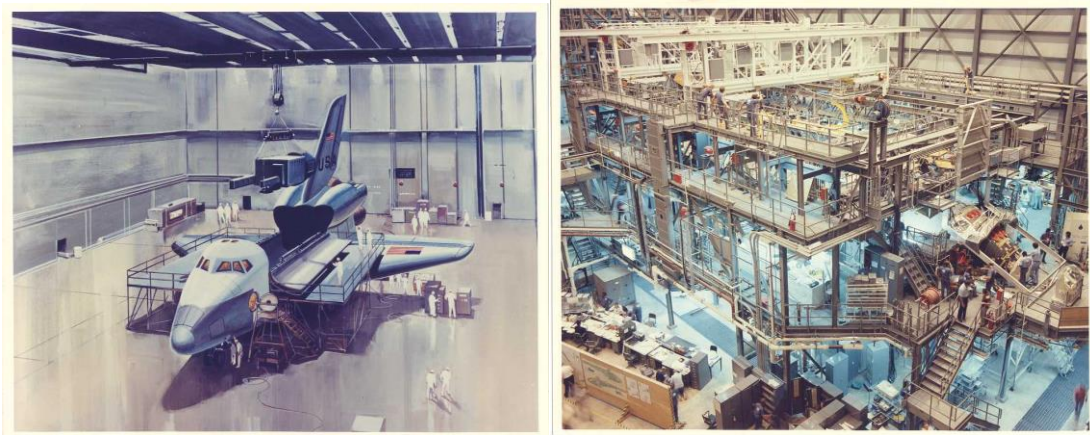
The NESC team concurs with the Air Force that the F-22 incidents can be attributed to several factors: 1) the high concentrations of oxygen at lower altitudes; 2) the inevitable acceleration which compounds the effects of high oxygen; 3) restricted breathing due to the inappropriate inflation of the upper pressure garment; and 4) contribution of uncharacterized F-22 life support system vulnerabilities, such as pressure drops [across] components in the cockpit.

The NESC team found a number of issues with the systems providing breathing air to the pilot. These systems are often treated as separate, but the events experienced are a result of the complex interactions of these systems, which, with the pilot included, are even more complex. Each flight puts extreme physiological demands on the pilot. The F-22 pilot community has come to consider a number of physiological phenomenon (*sic*) as a normal part of flying the Raptor, such as the difficulty in breathing and the Raptor cough. Acceptance of these phenomena as normal could be seen as a normalization of deviance.

The NESC team found no evidence of a contaminant producing a toxic exposure. However, in any jet fighter environment, irritant compounds can be present. The F-22 has no effective filtration of breathing air or cabin air, which means irritant compounds could potentially enter the cockpit.

C.2 Shuttle Ground Processing: HSI Experience

The Space Shuttle was “sold” to the American people and to Congress as a cost-effective way to get to/from low earth orbit (LEO). One of the primary selling points was that the Space Shuttle fleet could attain a launch rate of 40 round trips per year. This would provide remarkable and unheard of access to LEO. This rate would require that the ground processing turnaround time be on the order of 5 weeks for a fleet of 3 vehicles. The gap between the concept of operations (ConOps) for ground processing and the actual ground processing of the Orbiter is shown with remarkable clarity in Figure C.2-1, Shuttle Ground Processing: Conceptual vs. Actual.



Source: Bo Bejmuk, Space Shuttle Integration (Lessons Learned Presentation)

Figure C.2-1 Shuttle Ground Processing: Conceptual vs. Actual

The concept for ground processing was not unlike that of a jet aircraft. But the actual facility required extensive scaffolding to protect the delicate systems and wiring, thermal tile system, and several other systems that required special care and attention while allowing close proximity to the vehicle for the large numbers of workers needed for Space Shuttle Orbiter refurbishment. The problems with the Shuttle Development were classic:

- Insufficient definition of operational requirements during development phase
- Concentration on performance requirements but not on operational considerations
- Shuttle design organizations were not responsible for operational cost
- Very few incentives for development contractors to address maintainability or turnaround time.

Results:

A very labor intensive (high operational cost) vehicle was developed and put into operations.

The Lessons Learned:

- Must have the ConOps defined and applicable to all aspects of a system's life cycle (e.g., maintenance and ground turnaround as well as on-orbit operations).
- Levy the requirement on contractors to support the ConOps.
- Must have continuity and integration between designers, ground operations, and flight operations requirements during the development phase.

C.3 F-119 Engine: HSI Experience

Summary

The ATF program was created in 1981 to create a military jet that would guarantee air superiority. Two contractor teams competed for the fighter contract. In 1991, the ATF contract was awarded to the Lockheed team's F-22, powered by Pratt & Whitney's F-119 engine. This award was based in part on the fact that the F-22's engines offered superior reliability and maintainability. (Cost Estimation of HSI, Kevin Liu, 2010)

This came about because the USAF placed an emphasis on reliability and maintainability from the beginning of the ATF program, considering that over 50 percent of the USAF budget was devoted to logistics and predicted to worsen. Pratt & Whitney chose to emphasize designing for the maintainer throughout all aspects of the program and conducted ~200 trade studies as contracted deliverables. They also conducted thousands of information trades for internal use.

As a result, the F-119 engine could be maintained with only 5 hand tools and all line replaceable units (LRUs) were "one-deep," i.e., replaceable without removal of any other component. Furthermore, the LRUs could be removed with a single tool within a 20-minute window, even while wearing hazardous environment protective clothing.

Additional Detail

This HSI positive outcome case studies actions leading to the selection of Pratt & Whitney's F-119 engine for the Lockheed F-22 Raptor aircraft. Although this 1980-90s example pre-dates formation of the Air Force HSI Office at the Pentagon and subsequent formalization of HSI implementation, this well-documented example has served as a best practice case study for Department of Defense (DoD) HSI. (For additional information see "Cost Estimation of Human Systems Integration," Kevin K. Liu, Masters of Science thesis at Massachusetts Institute of Technology [MIT], June, 2010).

Overview: In November 1981, the ATF program was created to design a military jet able to guarantee air superiority against the Soviet Union. In 1983, a Lockheed/Boeing/General Dynamics team contracted into competition with Northrop Grumman. In 1991, the ATF contract was awarded to the Lockheed team's F-22, powered by Pratt & Whitney's F-119 engine (see Figure C.3-1). An important consideration in the contract's award was that the F-119/F-22 demonstrated superior supportability and maintainability.



Figure C.3-1 F-119 Engine Cutaway (Pratt and Whitney, 2002)

Context: When the F-22 program was approved in 1981, the Air Force placed an early emphasis on supportability and maintainability and maintained this emphasis throughout the program's life cycle. In June 1983, the Army, Navy, and Air Force signed a joint agreement to emphasize to the defense contractor communities the critical importance of improving operational readiness and supportability. At that time, system logistics costs were over 50% of the total Air Force budget and rising. The two prime competitors for the F-22 contract—Lockheed with Pratt & Whitney as their engine developer, and Northrop Grumman with General Electric (GE) as their engine developer—were first notified of the DoD's sustainability concerns.

The customer identified a priority on HSI in their requirements: In 1984, to address the growing escalation of systems logistics expenditures, the Air Force created a Reliability, Maintainability & Sustainability (RM&S) program. Besides reducing life cycle cost (LCC), the RM&S program sought to address reliability and durability problems that had plagued engines powering the existing Air Force's F-15 Eagle. Developed in the 1970s, the F-15 was specifically designed to counter the Russian MiG-25, with requirements emphasis placed on performance not RM&S.

Unfortunately, the high performance of the F-15 engine meant that it was more prone to failure and downtime. By the 1980s, the Russian air superiority threat was no longer as pressing, the growth in logistics costs was deemed unsustainable, and supportability began to be emphasized over performance. As a result, the Air Force wanted improved RM&S not only on the engine for the F-22, but on the system as a whole. Specific supportability goals for the F-22 were defined by the RM&S program and announced to the prime contractors. These included reducing the parts count, eliminating maintenance nuisances such as safety wire, reducing special-use tools, using common fasteners, improving durability, improving diagnostics, etc.

Understanding customer needs: Pratt & Whitney decided to center its competitive strategy on RM&S superiority, understanding the customer had made RM&S critical to the competition. For the F-119 engine, Pratt & Whitney decided not only to meet the Air Force's RM&S requirements, but to emphasize designing for the maintainer throughout all aspects of the program. The company's approach exemplified the best practices of what is now known as HSI.

Pratt & Whitney conducted approximately 200 trade studies using evaluation criteria such as user safety; supportability; reliability; maintainability; operability; stability; and manpower, personnel, and training. Figures of merit were developed for the trades to determine which human-centered disciplines should participate in each trade study. Pratt & Whitney also brought their engineers to Air Force maintenance facilities so that the engine designers could experience first-hand the challenges created for maintainers by past designs. Maintainers showed how tools were poorly designed, manuals had unclear instructions, and jobs supposedly meant for one person took two or more to complete safely. Lessons learned were passed on to every engineer on the F-119 engine design team and ground rules for maintenance design were established. Integrated Product Development (IPD) teams were established so that multiple, diverse discipline experts worked side-by-side on the design. Design changes were approved by a Configuration Control Board (CCB) of senior engineers from multiple technical disciplines. Design review processes ensured the work of one group did not create unforeseen problems for another. Proactive leadership made certain that HSI principles were followed.

One of the most important requirements for the F-119 was that only five hand tools be needed to service the entire engine. (In the end, the F-119 engine required five two-sided hand tools and one other, for 11 tools total.) Other requirements included: all LRUs were to be serviceable without removal of any other LRU, and each LRU was removable within 20 minutes. Subassembly drawings required annotation with the tools needed for service. Maintenance must be possible while wearing hazardous environment clothing. Maintenance tasks must accommodate maintainers in the 5th percentile female to the 95th percentile male range. Built-in test diagnostics were to eliminate the need for special engine diagnostic equipment. Training was computer-based.

To verify the maintainability of their design, Pratt & Whitney developed several full-scale mock-ups of the F-119. Though requiring a significant investment this ability to intimately evaluate the human/system interaction with maintainers allowed engineers to confirm their designs achieved maintainability goals.

HSI efforts contribute to competition success: In 1991, both Pratt & Whitney and GE were awarded contracts worth \$290 million to build prototype engines for flight evaluation. GE chose to emphasize the flight performance of its F-120 engine over RM&S, though the F-120 did meet the Air Force's RM&S requirements. Despite the F-120's superior performance in the air and higher thrust-to-weight ratio, on April 23, 1991, the Air Force chose the combination of Pratt & Whitney's F-119 and Lockheed's YF-22 to be developed into the F-22. Pratt & Whitney had demonstrated a better understanding of the Air Force's RM&S needs, having invested more time and money into HSI demonstration than had GE. Pratt & Whitney had presented a management plan and development schedule that the Air Force considered sensitive to their needs. On August 2, 1991, contracts worth \$11 billion were awarded to Lockheed and Pratt & Whitney demonstrating the Air Force's strategic investment in and commitment to HSI.

Key HSI success factors: The actions of both the Air Force and Pratt & Whitney were examples of top-level leaderships' role to sound HSI and SE practices. From a SE standpoint, the Air Force set formal requirements and expected product trade studies based on HSI concerns. At the program's outset Air Force leadership set clear supportability goals, explained their intent, and funded programs to show prime contract engineers actual Air Force maintenance conditions. Pratt & Whitney embraced processes that supported sound HSI outcomes and included diverse disciplines in major design and configuration decisions. Pratt & Whitney leadership invested in mock-ups, conducted testing, and held engineers accountable for RM&S standards, all of which led to HSI success. These combined efforts of customer and contractor to define clear requirements and communicate common expectations led to success.

The efforts described above can be summarized into several key HSI success factors:

1. Air Force policy to elevate HSI early in acquisition and development.
2. Design and trade studies that included HSI domains and cross-domain integration.
3. HSI's early inclusion in the contractor's SE methodology.
4. Participation with Air Force maintainers to understand their practices and challenges.

Insights into HSI's success in this case study:

1. The Air Force put their desired outcome into practice via formal HSI deliverables and requirements.
2. The IPD teams engaged HSI domain expertise in system design and the CCBs ensured multi-disciplinary management oversight. (IPD teams are more recently referred to as IPTs, now a hallmark of sound SE practice.)
3. Pratt & Whitney's early commitment to embrace HSI in their SE and project management practices defined the system from concept through flight test.

C.4 Constellation Program: HSI Experience

Following text adapted from: "Human Systems Integration (HSI) Case Studies from the NASA Constellation Program," S. Baggerman, D. Berdich, M. Whitmore (Human Systems Integration 2009).

There was no NASA agency-wide or even center-based deployment of the term HSI, or an associated definition. However, the inclusion of the human as part of overall system performance was not only recognized, but supported by the agency.

The NPR 8705.2B, Human-Rating Requirements for Space Systems (w/change 4 dated 8/21/2012) contained a set of technical requirements that establish a benchmark of capabilities for human-rated space systems.

The CxP 70024E, Constellation Program Human-Systems Integration Requirements document was developed specifically for the Constellation Program (CxP) from NASA Standard 3000, or NASA's Man-Systems Integration Standard, and provided a key mechanism for Constellation to achieve NASA's agency-level human-rating requirements.

Human systems integrators at the Johnson Space Center (JSC) and other centers across the agency were involved not only with the allocation and interpretation of the HSIR and with the human rating certification process, but also with the processes associated with human centered design and HSI. They worked with SME to ferret out cross-cutting issues that could affect the crew.

HSI worked with vehicle and habitat designers who ensured that HSI issues were included in trade studies and analyses to determine how best to balance vehicle and mission design while meeting the needs of the crew and considering human health and performance limitations. They used HSI tools and practices to mitigate the risks to mission and crew and to optimize vehicle design.

Work began to standardize the processes, tools, and techniques used to support HSI, as well as developing a definition or culture aimed at formalizing the term HSI and its practice as a NASA discipline. HSI had an evolving definition steered through benchmarking outside of NASA, also rooted in NASA's history, and due in great part to the emerging needs of current programs and projects.

HSI practitioners were heavily involved in the Constellation Program and Projects on many levels. The Crew Exploration Vehicle (CEV) Project also formally recognized a NASA HSI lead who integrated human health and performance concerns by leading or participating in integration forums to coordinate related technical issues with implementers, stakeholders, and subject matter experts in order to characterize risks and potential or realized system impacts, and to provide review of developing designs and architectures.

Within the Constellation Program's System Engineering and Integration (SE&I) Office, a Human Systems Integration Group (HSIG) was established with responsibility and authority, and accountability equal to other discipline area Systems Integration Groups (SIGs). The HSIG led human system integration across Projects for both hardware and software for all Constellation

crewed space systems, including the operability and usability of interfaces and hardware and software requiring human/operator interactions by the flight crew during ground and flight operations, as well as ensuring cross-systems, cross-mission support of human health and performance, including crew habitability accommodation and human interfaces. The HSI also acted as the book manager of HSIR.

A Human Systems Integration Technical Forum was established with the HSI to provide interpretation of HSI requirements and verifications methods.

Much work still lay ahead to standardize HSI processes, as well as products or required deliverables, which are less reactionary and more proactive in terms of Program and Project Management, and are more systematic.

NASA human systems integrators made much progress within the Constellation Program and Projects to mitigate risks to mission and crew, and to promulgate consideration of human health and performance in design and throughout the system life cycle, especially in light of a lack of formal recognition of the discipline area or a widely accepted definition of HSI. There were multiple agency-level documents that required human health and performance to be considered in spacecraft and mission design, enabling human systems integrators to contribute to the CxP. Most HSI efforts were at the grass roots, or bottom-up level, however, and were successful due to the nature of the integrators and subject matter experts themselves as much as due to the practices they used.

Following text adapted from: "Human Systems Integration (HSI) In Practice: Constellation (CxP) Lessons Learned," (2011) J. Rochlis Zumbado

Human concerns are currently integrated into NASA Development programs primarily through Requirements and Verification.

NASA agency-level document drivers:

- NPR 7120.5E – Space Flight Program and Project Management Requirements
- NPR 7123.1B – NASA Systems Engineering Processes and Requirements

HSI domains are not covered in a single requirements document, and in some cases, they are not covered at all:

- Based on the design reference mission (DRM), program-specific requirements are developed from the standards and invoked by the Human Rating NPR 8705.2B.
- NPR 8705.2B: 2.3.8 Human-System Integration Team. In 2011, no other Agency NPR calls for "HSI." To date, this NPR has only been applied to CxP, and there were lessons learned and best practices revealed.

HSIG was a part of Integrated Systems Performance under the SE&I Director for CxP:

- Co-Led by JSC Engineering and (now) Human Health & Performance Directorate
- HSIG managed the HSIR and was responsible for the human systems content in the Human Rating Certification Package.
- Performed horizontal technical integration of human systems concerns across the projects
- Resolution of human system technical issues used a community of practice (CoP) influence model.
- Consisted of Subject Matter Experts (SMEs) and representatives from all stakeholder organizations
- CoP method was a success story in terms of bottoms-up technical integration, but not without its limitations.

The CoP Model Facilitating Technical Issue Resolution:

- The CoP was used to facilitate resolution of technical issues.
- Program to Project teaming and coordination led to better vertical integration.
- Consolidation of technical positions was enabled at the discipline level and provided decision boards with integrated assessments.
- Collaboration of SMEs from across Agency, industry, and academia helped to:
 - Find the best expertise, regardless of location, and helped educate the community as to who the experts are and where they reside
 - Bring to bear the full breadth of this expertise within the technical disciplines to solve complicated issues
 - Disseminate expert knowledge and actually advanced the volume of knowledge in particular disciplines
- However, there were issues with a CoP implementation of HSI:
 - Decisional authority resided above the CoP, which made design decisions difficult to drive from the CoP level.
 - No single Technical Authority owned or represented HSI.
 - Authority intended for Human Systems Integration Team (HSIT) was not realized within the CoP model.
 - Human systems concerns often confused with JSC Astronaut Office input.
- CoP Lessons Learned & Best Practices:
 - CoPs were effective at resolving technical integration issues.

- Participation in the CoP across all levels is necessary.
- Management must engage the CoPs directly when solving problems and seek CoP input when making decisions.
- Organizational structure, and previously mentioned responsibility and authority issues are a factor here.

Roles, Responsibilities & Decision Making in Projects & Programs: Lessons Learned & Best Practices:

- Organization should be established very early in the life cycle with clear definitions of Roles, Responsibilities, Accountability and Authority (RRAA).
 - HSI team should be among the functions represented within the program structure.
- Provide the Authority to match the Accountability.
- Architect the decision making process.
 - Provides clarity and supports RRAA's between Program & Projects
- Ensure board representation is knowledgeable and empowered to act on behalf of those they represent.
 - Seek the input of the appropriate integration groups.
- Drive down decision making to the lowest level as long as potential system to system impacts have been considered and cleared. To do this, check:
 - Who is Responsible?
 - Who is Accountable?
 - Who needs to be Coordinated with?
 - Who needs to be Informed?

After CxP, NASA is changing the way it does business:

- Suggest moving from a standards-to-requirements approach, to process driven:
 - Provide guidance on what to do, how to do it, and by which milestones.
 - Prescribe less and advise more.
- Promote cross-directorate interaction in support of establishing an HSI vision, methodology, and implementation plan.
- Address the lack of formal structures that promote cross-directorate diversity of ideas.

To Achieve the HSI Vision at NASA:

- Commitment from Agency level of the importance of HSI and its role in project design, development and operation
- Development of HSI processes, practices and tools that can be implemented on projects of varying scales, as well as commercial ventures
- Ownership of HSI activities, from development of an HSI plan through to design and operations, along with the appropriate authority and management responsibility
- Not just about adding HSI integrators to projects, the goal is to have Project Managers thinking like HSI integrators

Following text adapted from: "VSM Activity Debrief: Constellation Program Lessons Learned," M. Whitmore, L. Pickett, J. Adolf, G. Vos (2011).

CxP Human Factors team captured lessons learned (successes and challenges) related to HSI processes and requirements associated with the CxP.

Key items that were done well:

- HSI disciplines were represented by project system managers in Orion.
- Did not stove-pipe within the supporting directorate – we effectively integrated our expertise within multiple engineering groups.
- Obtained good visibility in CxP projects. Joined the project teams and worked with them in design. Not equal engagement in each project, but well engaged across CxP.
- Having clear requirements got HSI at the table when projects were being created, and opened the door for HSI.
- An HSI scorecard was a very useful tool. Even though it was not a formal project deliverable, it was effective at tracking and obtaining integration with various project systems.
- Several HSIR requirements were significantly challenged in the beginning, but were effectively addressed and refined as CxP progressed.
- Process documents created to provide prime contractors with test and evaluation methodologies were very useful.
- Task analysis (TA) worked very well and proved itself as a valuable and effective planning and Test and Evaluation (T&E) tool. Phase based TA worked well to understand the vehicle with SMEs, and developed useful information for system maturation.

Core opportunities for improvement:

- An executive-level HSIT as required by NPR 8705.2B was never created, and the cross collaboration amongst existing forums and working groups lacked a single point of approval/rejection for HSI issues of consideration.
- Roles and responsibilities (R&R), including programmatic guidance, should be formally established as soon as possible, and not allowed to remain ambiguous. Issues related to R&R pervaded both project working groups as well as internal Human Health and Performance Directorate interactions. A hierarchical command structure with checks and balances should be considered.
- Program and project constraints drove multiple technical review issues associated with resource allocation, limitations on resolution of review comments, and limited time for effective document and design review. Programs should ensure they provide adequate time for technical milestone reviews.
- Programs such as CxP have a significant and unaddressed need for pre-acquisition work so that HSI deliverables are included. CEV Project had planned such a deliverable, but it was removed by the project, an action that critically limited HSI authority.
- HSI requirements should focus on performance criteria, and avoid design specification.
- Several HSIR verification requirements exceeded their parent HSIR requirements.

Actionable Recommendations Executable within Human Health and Performance Directorate:

- Generate an implementation plan of how HSI operates and integrates with projects and programs. The plan should be mapped to NPR 7123.1B milestones and criteria.
- Roles and responsibilities (R&R), including programmatic guidance, should be formally established as soon as possible, and not allowed to remain ambiguous. A hierarchical command structure with checks and balances should be considered.
- HSI requirements should focus on performance criteria, and avoid design specification. Simplify requirements to the extent possible and allow Subject Matter Experts (SMEs) to provide design and development guidance when needed.
- When working with design groups, focus on what is needed so that projects can understand and support the requirement.
- Some HSIR requirements need revision/maturation (e.g., suited anthropometry, strength, response time). Consider a requirements review to identify requirements/verifications needing further work.
 - Often verification requirements need more refinement than parent requirements.

- Some verifications have potential scoping issues, which need to be addressed. The verifications in some cases need to be scoped to an achievable process allowing verification in an affordable way.
- Some verifications exceeded their parent requirements.
- Need a focused group to ensure early HSI engagement both on pre-acquisition work on projects and associated integration efforts.
- All requirements are not equal in importance, but HSIR is structured and presents them that way. Need an indented structure to indicate priority for requirements.
- Utilize lessons learned in risk identification, benefit/cost analysis, and asking management to make decisions based upon inclusion of all factors and options.

Actionable Recommendations Executable with Community Support:

- A full HSIT with tech representation per NPR 8705.2B is needed, with the top level HSIT existing irrespective of any specific project and program. Program and project representatives to the HSIT would be appointed as new programs and projects are brought into existence.
 - This relates to multiple CxP issues, including oversight of HSI requirement revisions, dispute resolution regarding requirement interpretations by projects, and determination of project specific tailoring or implementation letters.
- Programs should ensure that prime contractors provide adequate time for technical reviews.
- Programs such as CxP have a significant and unaddressed need for pre-acquisition work so that project deliverables are included to ensure HSI inclusion and integration.
- Programs should be established before their child projects.

Next Steps Near Term:

- Establish an institutional HSIT at JSC or at a directorate level.
- Initiate strategic work on Human Readiness Level/Human Rating Assessment tools, HSI roles in certification of flight readiness for human flight tests, etc.

Forward Work Items:

- Push for establishing an Agency level HSIT as required by NPR 8705.2B.
- Develop a formal lessons learned process to efficiently capture, disseminate, and utilize lessons learned for continuing work and future programs.

- Provide detailed interview / survey data to HSI implementation leads/managers.
- Leverage these detailed lessons learned findings to improve HSIR.
- Leverage these lessons learned to refine HSI interaction for continuing CxP projects.
- Feed forward lessons learned into commercial HSI implementation and future programs.
- Continue efforts to leverage DoD HSI best practices and implementation.

C.5 HSI Ideal State for Future Large Scale Human Space Flight Program

An ideal future NASA implementation of HSI must fully embrace the key concepts noted in section 1.4 of this document.

Following is a high-level overview of what an ideal NASA HSI process should entail:

- 1) In conceiving new systems, missions, or technologies, ideas spring from recognizing the successes and limitations of prior operational accomplishments. NASA's early human space flight program followed a logical sequence of operational demonstrations that ultimately led to sending three crewmembers to the moon and landing two of them on the surface. The DoD serves as a current example of continual operational assessment and process improvement. For the DoD, experience in the combat arena continually leads to experience-based conceptualization of new system designs or enhancements—i.e., “if only we could do <new idea>, we could be more successful when this situation arises.” In short, embrace the perspective that operational experience germinates new system concepts. Then the implementation and execution of HSI—i.e., the strategic mission of HSI—then becomes clearer: Ensure that the original operational vision is implemented.

Section 4.4.1.2, Design Solution: Process Activities, of NASA/SP-2007-6105, Systems Engineering Handbook, discusses some of the challenges of maintaining a focus on the original vision for a new system:

“Once it is understood what the system is to accomplish, it is possible to devise a variety of ways that those goals can be met...Ideally, as wide a range of plausible alternatives as is consistent with the design organization's charter should be defined, keeping in mind the current stage in the process of successive refinement. When the bottom-up process is operating, a problem for the systems engineer is that the designers tend to become fond of the designs they create, so they lose their objectivity; the systems engineer often must stay an “outsider” so that there is more objectivity. This is particularly true in the assessment of the technological maturity of the subsystems and components required for implementation. There is a tendency on the part of technology developers and project management to overestimate the maturity and applicability of a technology that is required to implement a design. This is especially true of “heritage” equipment. The result is that critical aspects of systems engineering are often overlooked.”

The HSI practitioner can provide ongoing program or project (P/P) objectivity through continually insisting on validating the question, “Are we building the system originally envisioned?” Why would HSI perform this role? An assessment of prior program cost-escalation and “mission creep”—i.e., a loss in focus from the original vision and mission—would likely indicate that it was often late consideration of the inter-relationship of hardware/software systems with P/P human elements that led to issues. See the examples in appendices C.2 on Space Shuttle and C.3 on the F-199 engine.

- 2) The NASA SE process outlined in NPR 7123.1 and NASA/SP-2007-6105 break the life cycle of a P/P into distinct phases. An overview of these phases can be found in section 3.1, Engine Processes Overview, of this document. For successful implementation of HSI, it is essential that HSI engage from the earliest outset of a program or project—i.e., HSI is integral to Pre-Phase A, Concept Studies. At this earliest formalization of a P/P, the NASA SE process requires development of the ConOps—Concepts of operation and scenario development. The ConOps is a more detailed and documented vision of how the total system is to perform in the operational arena. The ConOps should address both nominal and off-nominal mission/system scenarios.

Additional tools can and should be brought to bear to refine the ConOps, notably human/system task analyses, clear functional understanding and allocation of tasks the hardware and software are to perform vs. the tasks human operators/controller/maintainers are to perform (i.e., “function allocation” in brief), and clearly planned or envisioned allocation of roles and responsibilities among the human elements required to make the system operational. Note that all of these processes are mentioned in both NASA SE documentation and in the Human-Centered Design requirement in NASA-STD-3001, NASA Space Flight Human System Standard. In performing these early concept clarifying efforts, maintaining the focus on the human element is the critically unique attribute of HSI. In short, in Pre-Phase A, HSI must take the original operational vision for the system and codify it into formal P/P performance goals. The HSI practitioner should strive to establish goals—i.e., SE Key Performance Parameters (KPPs)—that can be objectively tracked through the rest of the system’s life cycle. Examples might be: size of the ground control contingency; reliance on autonomy vs. ground control; maintenance ConOps and repair strategy (e.g., tool set size, spares supply, manufacturing in place, skills required, training, etc.);

- 3) In Phases A and B of the NASA SE process, the system design takes shape and trade studies are performed to select the final hardware/software design that will be built. Of course, every design decision has implications for the total system performance. Particularly for the HSI perspective, every hardware/software design decision has implications for human interaction with the system. During design, it is imperative that these impacts are continually assessed and evaluated against the original P/P goals for the human element. Are there impacts to safety? To mission effectiveness or efficiency? To the numbers and skills of personnel contingents required to make the system operational? To training? To the total population of personnel accommodated by the system?

P/P HSI practitioners and implementers of the HSI Plan must continually press for an iterative approach to conceptual design and to prototype or model the system with the intent of performing human-in-the-loop (HITL) evaluations that ensure the HSI KPPs for total system performance are on track. The HSI KPPs themselves may be re-validated during system conceptualization and design and new KPPs may appear. This is one reason the P/P HSI Plan is intended to be a living document that is updated at major life cycle milestones. These processes remain consistent with currently NASA-documented SEg and human-centered design methodologies.

- 4) If appropriate and thorough HSI has been applied through Phase B of the life cycle, the remaining effort entails that the HSI practitioners track and verify the HSI goals through development and into the operational arena.

Though several key document changes have been made in recent years to support implementation of this HSI process overview, there is still much work to be done. Examples of forward work include (but are not limited to):

- There is no formal mandate in any NASA documentation that requires application of HSI to program or projects.
- Much existing NASA human factors documentation focuses only on the human factors of flight crew interaction with flight systems, not the interactions of all personnel who interact with a system throughout its life cycle.
- Much existing human factors and human-rating NASA documentation focuses on human space flight programs and projects but HSI is fully applicable to unmanned space flight and to aeronautics programs and projects.
- There is considerable human factors engineering, habitability, and environmental factors NASA documentation but other aspects of HSI—e.g., maintenance, logistics, training—need to be as thoroughly addressed.
- No NASA Headquarters level organization currently enforces the application of HSI, or holds responsibility for establishing a cohesive, consistent approach to Agency implementation of HSI.

Another example of forward work for the HSI implementation is Model-Based System Engineering (MBSE). It is approached as a special topic in the 2015 update material to NASA/SP-2007-6105 that looks forward to a higher degree of formal rigor in system modeling and analysis, enabled through virtually integrated, comprehensive system models (rather than disconnected, partial models). It will also entail a model-centric versus document-centric method of system design and development. For the HSI team, MBSE will present a significant challenge, even beyond the challenge to SE in general, to develop and integrate human analytical models into the larger system model. The wide range of variability in human physiological function and behavioral performance and the extreme complexity of the interactions among many human physiological and cognitive functions may be very difficult to capture and to represent in models that can be connected (via automation) to other parts of a comprehensive system model. In an ideal-state P/P, the abstraction of key human characteristics may be a useful technique to generate HSI models that can become parts of an entire MBSE system model; however the SME expertise within all HSI domains will continue to be critical to inform the effective design of missions and systems that are compatible with human populations.

Another example of the future ideal state of HSI practice is an expanded program of HSI training available for both the HSI Practitioner and for the P/P Manager. The NASA SE curriculum should be expanded to add these courses.

For the Practitioner (and HSI team members), the training should include a series of courses similar in concept to the Naval Post Graduate School's HSI Certification Program. These could include the following topics:

- **COURSE 1: Introduction to Human Systems Integration.** The policies that govern HSI, the domains that comprise HSI, and the capabilities and limitations of humans in complex systems under a variety of stressful conditions.
- **COURSE 2: Human Systems Integration in the Acquisition Lifecycle.** How HSI practitioners work with developers, designers, program managers, logisticians, and engineers to influence the entire life cycle of a system – from concept development through the operations and support phase.
- **COURSE 3: Human Systems Integration Tools, Tradeoffs, and Processes.** The theories and tools to help HSI practitioners to assist acquisition program leaders in making trade-off decisions in a resource-constrained environment.
- **COURSE 4: Human Systems Integration Case Studies and Applications.** Application of material learned in the previous three courses to evaluate historical case studies and to engage in HSI activities in typical acquisition systems.

For the P/P Manager, a condensed HSI course will be ideal, to provide this individual with a broad overview of HSI, its purpose, and specifically its value to the P/P in terms of outcomes (cost, performance, schedule).

Some of the key aspects of an HSI ideal state are:

- **Institutional and Program Management Principles:**
 - Recognize the human elements of the mission-system as critical to success.
 - Focus on early human integration to achieve a life cycle return on investment.
 - Design to achieve best value from the humans who are critical to the mission.
 - Balance human-system risks as major elements of all risk inherent to the program.
 - Make decisions with a long-term view of all phases of development and operation.
 - Leverage the Agency's human research and technology foundation.
- **Program Culture:**
 - Value the distinct roles of all teams including HSI.
 - Implement the Agency's path for human space exploration.
 - Enhance leverage of knowledge captured from past programs.
- **System Engineering:**
 - Apply appropriate rigor to manage technical baseline and all associated risk.
 - Recognize Agency technical authorities' roles in technical/human requirements.
 - Conduct the SE Engine processes methodically to achieve program technical goals.
 - Empower a formal HSI Team within SE to conduct HSI processes.

- HSI Involvement:
 - Establish a firm basis of Agency infrastructure for application of HSI in programs.
 - Apply the HSI key tenets within the SE Engine environment.
 - Engage all essential HSI domains and subject matter expertise.
 - Conduct a rigorous integration of human with system software/hardware elements.
 - Implement risk balancing by meeting human health and performance standards.

Institutional Investment

When new NASA P/Ps are established and funded, full integration into P/P management and SE processes is the key to successful savings through HSI, including fulfilling HSI's cost-savings potential. Optimal integration requires high-level coordination among domain owners, facilitated by HSI practitioners working within P/P system working groups (communities of practice) and IPTs to obtain optimum solutions.

By working very diligently within P/P processes in a coordinated HSI framework arena, experts in human factors, crew systems, safety, and other relevant human-centered fields can better influence system designs to control human-related LCC growth, prevent the need for later hardware and software modifications for improved system operability and/or safety, and reduce late-stage discovery of HSI hazards due to lack of early human integration—the “fly and fix” or “test and fix” difficulties that have historically plagued the system acquisition process.

Institutionally, having well established HSI practitioners can be invaluable to decision making bodies, boards, and non-advocate review panels. Support for “head-turning” decision-makers who can ask “What do you think?” and receive an experience-seasoned answer must be preceded by an intuitional investment and ingrained in the engineering culture.

Taking the strategic view for human space flight in general, there are numerous future technical and human performance challenges to be faced in advancing NASA's vision and mission. Agency institutional HSI organizations need to not only to work to meet current P/P needs, but also to develop the capabilities, skills, and infrastructures to prepare NASA to meet long-standing strategic challenges such as learning to optimize human effectiveness and the efficient deployment of human assets in the design of complex systems. For example, a future human space flight mission to Mars will undoubtedly require a significant number of human-system trade-offs, evaluations of new concepts and designs to autonomously support human crews, and plus innovation in human/technical solutions that has as of yet not occurred. Building expertise in managing these processes is an investment that must be in place long before a particular P/P is initiated. Finding ongoing funding to build and maintain an infrastructure for HSI outside of current P/P resources will be a formidable challenge.

HSI Institutional Challenge

HSI challenges the traditional paradigm that a Program and Project budget can be separated between development and operational phases.

If the budgets are separated, then the PM managing the development may not optimize operational cost since it is “someone else’s problem.” And the PM managing the operations will inherit a suboptimal design, destined for work-arounds and high staffing.

The developing manager should be accountable to Life Cycle Cost containment and performance optimization across all phases.

C.6 Agile Development Brings New Challenges for Software Assurance at NASA

Capability Maturity Model Integration, the NPR 7150.2B-required method for critical NASA Class A and Class B software projects, is used heavily for defense and aerospace projects as a rigorous process improvement model. Its best practices necessitate both documented processes and evidence that the processes are being followed.

On the other hand, most “pure” agile development methods cycle through “sprints” — quick rounds of production followed by review. There is typically less documentation and the team learns as it goes.

“It’s an ideal approach in private industry, where you want to be first to market. You get your product out there and then you release updates,” said NASA Software Assurance Technical Fellow Martha Wetherholt. “But when you’re heading for one launch of one vehicle, where safety needs to be proved and documented, a straight agile approach may not be the best option.”

Wetherholt envisions NASA using an approach that combines elements of agile development with more traditional, plan-based development. Rigorous documentation is still necessary for NASA’s safety critical applications and functions. Software needs to be analyzed to see how it may be contributing to system hazards. Then, needed controls and mitigations need to be designed in and tested to make sure that the controls work as required. Also, software is often used to detect and mitigate hardware hazards; these software requirements and design changes also must be documented, designed in, and verified and validated to work. Software Assurance personnel need to provide evidence and proof that appropriate safety measures were taken.

Despite its challenges, agile development brings creativity and opportunity to NASA’s next-generation missions. In addition, many of NASA’s commercial partners use or will use agile development in their projects. To provide effective oversight, Software Assurance personnel must continue to adapt, learn and keep up-to-date with the latest software development processes, and software developers need to embrace Software Assurance as part of the agile process.

One such example is Marshall Space Flight Center’s (MSFC) Space Launch System (SLS) flight software team, which has been using tailored agile methods in combination with more traditional methods.

Software Engineering Process Group Lead Helen Housch (Cepeda Systems & Software Analysis, Inc.) described a tailored process where portions of the development life cycle are performed within sprints (agile methods), while others—such as overall planning, black-box requirements development, and final product integration—are done outside of the sprints.

The SLS team has had success with the agile development process, and has seen several improvements. Housch stated communication and coordination among requirements, design/implementation, and test teams have improved significantly, as teams work together to incrementally develop software and other work products.

The SLS flight software team's Software Assurance personnel participate in sprint review meetings and are involved in the sprints as they elect. Communication with external stakeholders including Software Assurance and senior management has also improved, as incremental development progress is more quantifiable and evident through post-sprint review meetings. Housch agreed that Software Assurance participation in the sprint activities is beneficial to the process.

"Incremental development allows the customer to see progress much earlier in the lifecycle," said Housch. "The traditional software development methods do not always allow customer and manager visibility into the progress until the end of the implementation phase. With agile, stakeholders are able to see progress at regular intervals (every six months or so) as software is developed and planned functionality is released."

A customized agile approach allows flexibility to tailor the project's processes to effectively and efficiently meet mission objectives. "No two organizations do agile exactly the same," said Housch. "The agile approach should be tailored to the goals of the organization that's performing the agile activities."

APPENDIX D REFERENCES

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D.2 NPDs and NPRs

The latest versions of these policy documents can be found in the NASA Online Directives Information System library at <http://nodis3.gsfc.nasa.gov> .

- NPD 1000.0B, NASA Governance and Strategic Management Handbook
- NPD 7120.4D, NASA Engineering and Program/Project Management Policy
- NPR 7120.5E, Ch. 13, NASA Space Flight Program and Project Management Requirements w/Changes 1-13
- NPR 7120.7, NASA Information Technology and Institutional Infrastructure Program and Project Management Requirements
- NPR 7120.8, NASA Research and Technology Program and Project Management Requirements (w/change 3 dated 4/18/13)
- NPR 7120.11, NASA Health and Medical Technical Authority (HMTA) Implementation
- NPR 7123.1B, NASA Systems Engineering Processes and Requirements
- NPR 7150.2B, NASA Software Engineering Requirements
- NPR 8705.2B Ch.4, Human-Rating Requirements for Space Systems, w/change 4 dated 8/21/2012
- NPR 8900.1A, NASA Health and Medical Requirements for Human Space Exploration

D.3 NASA Standards

NASA Technical Standards can be found under the “Other Policy Documents” menu in the NASA Online Directives Information System library at <http://nodis3.gsfc.nasa.gov> or at the Standards and Technical Assistance Resource Tool (START) <https://standards.nasa.gov/> ·

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